Riding Out Future Quakes

Pre-Earthquake Planning for Post-Earthquake Transportation System Recovery in the San Francisco Bay Region

OCTOBER 1997

ASSOCIATION OF BAY AREA GOVERNMENTS

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Publication Number: P97002EQK

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Acknowledgments:

ABAG would like to acknowledge the efforts of the following members of the Review Committee in reviewing the material which forms a basis for this document.

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The writing and production of this report was financed in large part by a cooperative agreement with the California Department of Transportation Agreement No. 4-1605-C, with additional funding by the Association of Bay Area Governments. Additional funding for disruption modeling was provided to ABAG by Grant No. 1434-HQ-96-GR-02723 from the U.S. Geological Survey (USGS). Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding agencies.

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BACKGROUND AND OBJECTIVES ...

The purpose of the research for this project was to assess the vulnerability of the region's transportation system to earthquakes as an initial step in expanding pre-earthquake planning.

The project was initiated by ABAG and Caltrans following the Northridge and Loma Prieta earthquakes for two principal reasons.

1. We are concerned about transportation problems immediately after earthquakes because emergency responders need to use transportation systems.
2. We now have an increased understanding of the role that transportation system disruptions can have on a region's economy for months, if not years.

We wish to minimize the impact of such disruptions by (a) developing hazard information – particularly relative to regional infrastructure – in map form, and (b) expanding cooperation, coordination and commitment among transportation providers and users for coordinated pre- and post-earthquake planning.

The current seismic retrofit program of Caltrans currently focuses on the retrofit of bridges and highway structures to prevent collapse. These structures have been retrofitted to minimize the likelihood of collapse and to prevent fatalities and injuries, but may still be closed for a period of time for repair of any damages.

The Loma Prieta and Northridge earthquakes served notice that we need to identify what is likely to be the surviving portion of our transportation system. Since Northridge, Caltrans has been working on adopting a system of lifeline routes that would facilitate movement between major staging areas and impacted areas following major earthquakes. For example, the Stockton and Tracy areas may serve as such staging areas for getting emergency supplies into an impacted San Francisco Bay region. In such a case, I-580 becomes critical. The results of this effort can also serve as analysis or programming tools for identifying future improvement needs for highway structures. In the Bay Area, Caltrans, the Metropolitan Transportation Commission (MTC) and the county congestion management agencies (CMAs) continue to work cooperatively to identify routes that are critical for life safety and emergency response, to examine routes that serve major roles in the economic recovery of the Bay Area, and to evaluate performance level needs for these routes and their structures.

At the same time, MTC, Caltrans, State and local Offices of Emergency Services, and transportation providers continue to coordinate their activities to develop an earthquake response plan which encompasses all modes of available transportation.

Caltrans had several objectives when it entered into the cooperative agreement with ABAG to develop this report and the associated materials:

1. To develop a long-term partnership among transportation providers and users, the earthquake research community, and earthquake responders to foster cooperation for response and recovery.
2. To assess the vulnerability of the transportation system given the scenario earthquakes considered reasonably likely for the San Francisco Bay Area, incorporating these data and results into a computer-based geographic information system (GIS).
3. To assist in identifying critical or non-redundant structures along the key corridor segments in the San Francisco Bay Area to facilitate pre-planned detours or to examine the feasibility of future upgrades to provide adequate post-earthquake functionality.
4. To provide increased public awareness of the impact a future Bay Area earthquake might have on our transportation system extending beyond bridge and highway structure damage to include faulting, landslides, building collapses, hazmat releases, and other direct and indirect impacts.
5. To serve as a model approach for other metropolitan areas.

Given that the probability of another major or catastrophic earthquake in the San Francisco Bay Area in the next ***ten*** years is ***one in three***, the rapid dissemination of existing data and research is essential. ***Let's make sure that we are prepared for the next earthquake disaster.***

SUMMARY...

We are speeding into a major transportation disaster after major future Bay Area earthquakes.

Our transportation system suffered extensive damage due to the Loma Prieta earthquake in 1989. There were 142 road closures, including the spectacular failures of the Cypress structure in Oakland and the Oakland-San Francisco Bay Bridge.

The Northridge earthquake in 1994 resulted in approximately the same number of closures – 140. Yet disaster operations were able to function, people were able to work, and the economy did not collapse.

There are at least EIGHT likely future earthquakes that will probably have more of an impact on the Bay Area's transportation system than either Loma Prieta or Northridge.

We are projecting far more extensive damage to our transportation system in future Bay Area earthquakes.

When the northern Hayward fault, extending from San Pablo Bay to San Leandro, suddenly ruptures ***we now predict almost 900 road closures – over six times those in Loma Prieta or Northridge.*** This magnitude 7.1 earthquake has a 28% likelihood of occurring in the next 30 years. [1]

When the peninsula segment of the San Andreas fault, located in San Mateo County, ruptures, ***428 road closures may occur – three times those in Loma Prieta or Northridge.*** This magnitude 7.1 earthquake, in a less urbanized area than the Hayward fault, has a 23% likelihood of occurring in the next 30 years. [1]

ABAG examined the effect of eleven possible future earthquakes on our transportation system. ***Eight*** of those earthquakes are expected to have much more of an impact on our transportation system than either the Loma Prieta or Northridge earthquake.

The project was initiated following the Northridge and Loma Prieta earthquakes with increased understanding of the role that transportation system disruptions can have in affecting the region's economy for months, if not years. Of more immediate concern, transportation problems immediately after earthquakes can impede the ability of emergency responders.

These past earthquakes were only driver's training for emergency transportation response planning in the San Francisco Bay Area.

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[1] The probability of future earthquakes information is from Working Group on California Earthquake Probabilities (1990). ***Probabilities of Large Earthquakes in the San Francisco Bay Region, California***: U.S. Geological Survey Circular 1053, 51 pp.

We used estimated closures due to TEN separate hazards.

The approach used in developing these estimates of transportation disruption and road closures examined ten different hazards:

1) surface rupture, or the rupturing of the ground surface due to faulting;
2) shaking-induced damage to freeway and road bridges and structures;
3) liquefaction, or the flowing of sandy soil;
4) earthquake-induced landsliding;
5) building damage, including building collapse or threat of building collapse;
6) water main ruptures severe enough to cause road closure;
7) natural gas releases severe enough to cause road closure;
8) hazardous material releases severe enough to cause road closure;
9) dam inundation closures, that is, closures due to both the actual or threat of dam failure (not considered a significant hazard at this time); and
10) other unusual or unanticipated causes.

ABAG's shaking hazard maps were crucial to this modeling effort.

The intensity maps are based on the most recent version of ABAG's ground shaking models, described in ***On Shaky Ground*** (Perkins and Boatwright, 1995). The scenarios examined include large earthquakes generated by:

- entire Hayward fault (both northern and southern segments);
- southern segment of the Hayward fault;
- northern segment of the Hayward fault;
- Healdsburg-Rodgers Creek fault;
- Maacama fault;
- peninsula segment of the San Andreas fault;
- San Gregorio fault;
- northern Calaveras fault;
- Concord-Green Valley fault;
- Greenville fault; and
- West Napa fault.

These predictions are based on the careful examination of data from past earthquakes.

The estimate of the impacts of future earthquakes on our transportation system are based on a careful analysis of data from the Northridge and Loma Prieta earthquakes. Because the predicted number of road closures is so large, an extra effort was made to check and recheck assumptions to ensure that the numbers are not systematically large. We are confident that these predictions are reasonable.

The results of this modeling effort, by county, are shown in the following table. The results of the models for the Loma Prieta earthquake, as well as the actual data from that earthquake, are provided for comparison.

TABLE 1: Predicted Road Closures for Bay Area Counties and Selected Earthquake Scenarios

County Data for Earthquake Scenarios	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	TOTAL
Loma Prieta - Actual (Bay Area)	25	2	0	0	72	6	9	0	0	114
Loma Prieta - Modeled	23	9	7	0	49	11	38	0	0	138[2]
Peninsula Segment of San Andreas	41	4	21	0	84	166	111	0	1	428
San Gregorio	20	3	23	0	55	104	10	0	1	216
Northern Hayward	506	213	47	2	85	10	14	8	10	894
Southern Hayward	602	31	31	1	55	9	69	7	4	809
Entire Hayward	851	227	52	3	228	19	79	12	14	1,484
Healdsburg-Rodgers Creek	43	22	40	4	51	4	3	9	178	354
Maacama	6	3	4	2	6	1	1	1	46	69
West Napa	16	20	4	70	6	2	2	15	5	140
Concord-Green Valley	52	164	4	13	11	4	10	74	4	337
Northern Calaveras	156	82	4	1	9	3	28	8	1	291
Greenville	63	31	4	0	6	2	8	10	1	124

Another way of expressing the model results is in terms of hazard causing the closures, rather than by county area. The results of this analysis are shown in the following table. Again, the results of the models for the Loma Prieta earthquake, as well as actual data from that earthquake, are provided for comparison.

[2] The principal reason for the apparent overestimation of road closure in the Loma Prieta earthquake is the assumption that there would be more earthquake-induced landslides in the future. Loma Prieta occurred in a dry October.

TABLE 2: Predicted Road Closures by Hazard for Selected Earthquake Scenarios

Hazard Data for Earthquake Scenarios	Fault Rupture	Shaking-Damaged Road and Highway Structures	Land-slides	Lique-faction	Building Damage	Water Main Ruptures	Natural Gas Releases	Hazmat Releases	Dam Inun-dation	Freeway Hazard	Other Hazards
Loma Prieta - Actual (Bay Area)	0	25	7	14	38	17	0	0	0	15	25
Loma Prieta - Modeled	0	24	24 (wet)	14	34	7	1	1	0	11	22
Peninsula Segment of San Andreas	103	60	41	28	72	24	5	2	0	27	67
San Gregorio	58	24	23	20	36	7	1	2	0	11	34
Northern Hayward	282	109	65	41	160	32	6	10	0	50	140
Southern Hayward	236	126	58	40	109	38	7	10	0	58	126
Entire Hayward	466	177	101	44	300	60	12	16	0	81	232
Healdsburg-Rodgers Creek	83	43	43	38	45	20	4	3	0	20	55
Maacama	22	9	12	1	5	4	1	1	0	4	11
West Napa	38	18	20	10	12	8	2	2	0	8	22
Concord-Green Valley	102	46	38	24	23	22	4	5	0	21	53
Northern Calaveras	81	49	32	20	16	18	4	3	0	23	45
Greenville	26	23	18	8	8	8	2	2	0	10	19

Our biggest problems occur when all or part of the Hayward fault ruptures.

In both these tables, it is important to note the huge number of predicted road closures if the entire Hayward, northern Hayward, or southern Hayward scenarios occur relative to the other eight scenarios.

These loss estimates are based on models which could be improved in the future with more information.

The emphasis of this effort has been to take available information on highway structures, road locations, and hazards, and then to combine them with models to predict hazard exposure. These estimates could be improved in the future based on additional research.

Some additional factors are not addressed by the modeling.

Note that this modeling process does not include:

- secondary disasters (such as huge fires, toxic gas releases far larger than Northridge or Loma Prieta, or dam collapse);
- possible road closures created to locate emergency housing; or
- extensive ground failures due to ground saturation associated with a very large winter storm.

In order to plan for the use of our transportation system immediately following an earthquake and for long-term recovery, the users of that system, their locations, and where their facilities are concentrated were identified.

Key transportation users in emergencies include

- air transportation facilities,
- marine transportation facilities,
- rail transportation facilities,
- transit facilities,
- emergency health care facilities,
- fire, police and emergency operations centers,
- public mass care (including both feeding and sheltering),
- water supply facilities,
- wastewater treatment facilities,
- electric power and natural gas facilities, and
- communications facilities.

The facilities are concentrated along a limited number of key transportation corridor segments, including:

- I-880 from State Route 24 / I-980 to east State Route 238 / I-580 (the south Oakland corridor segment);
- I-80 from State Route 24 / east I-580 to State Route 4 (the north Oakland/Berkeley/Richmond corridor segment);
- I-80 over the San Francisco - Oakland Bay Bridge;
- State Route 101 from San Francisco to the Dumbarton Bridge (the Peninsula corridor segment);
- State Route 1 from Half Moon Bay north to San Francisco (the San Mateo County coast corridor);
- I-580 from I-680 east to State Route 84 in Livermore (the tri-valley corridor);
- I-680 from State Route 24 in Walnut Creek north to the Benicia-Martinez bridge (the northern I-680 corridor);
- I-580 from I-80 in Richmond to State Route 101 in San Rafael (including the Richmond-San Rafael Bridge); and
- State Route 101 from San Francisco to State Route 37 in Novato (the Marin - 101 corridor segment).

Thus, from a planning perspective, these nine corridors have the greatest priority for pre-earthquake planning, particularly during the first few days following a major earthquake.

We can combine the information on road closures with these key transportation corridors to identify critical vulnerabilities in our current transportation system.

The results of this extensive analysis of the potential closures of roads, together with these key corridor segments, points to several vulnerabilities in our current transportation system.

- the south Oakland corridor segment in any of the three Hayward scenario events;
- the north Oakland/Berkeley/Richmond corridor segment in any of the three Hayward scenario events;
- the Bay Bridge and, particularly, its east-Bay approaches in all of the scenarios except the Maacama, West Napa, and Greenville earthquakes;
- the Peninsula corridor in the San Andreas Peninsula scenario earthquake;
- the San Mateo County coast corridor in the San Andreas Peninsula and San Gregorio scenario earthquakes;
- the tri-valley corridor in the northern Calaveras and Greenville scenario earthquakes;
- the northern I-680 corridor in the Concord-Green Valley and northern Calaveras earthquakes;
- the Richmond-San Rafael Bridge corridor in all of the scenarios except the Maacama, West Napa, northern Calaveras and Greenville earthquakes; and
- the Marin - 101 corridor in the San Andreas Peninsula, San Gregorio, three Hayward, and Healdsburg-Rodgers Creek scenario earthquakes.

What do we need to do next?

As a follow-up to this study, transportation providers and planning agencies need to:

- ☑ hold corridor-level and scenario-specific workshops to help identify ways to mitigate the anticipated transportation impacts; and
- ☑ identify critical transportation facilities that need to be usable, or returned to service, immediately following an earthquake, as well as to help initiate the necessary future planning and improvement actions.

What can we do now?

Both transportation providers and transportation users need to consider this study's estimates of road closures, and make appropriate preparations. Some suggested planning actions are supplied as checklists in Appendix A of this report for:

- ☑ transportation providers;
- ☑ utilities;
- ☑ emergency services providers;
- ☑ local governments;
- ☑ private companies; and
- ☑ residents.

WHAT WERE THE STREET AND FREEWAY DISRUPTIONS IN THE LOMA PRIETA AND NORTHRIDGE EARTHQUAKES ?

Introduction

In order to understand the effects of future earthquakes on the transportation system, it is essential that we understand the past. Thus, ABAG collected and assessed the transportation impacts of the two most recent disastrous California earthquakes: the 1989 Loma Prieta earthquake, and the 1994 Northridge earthquake. The assessment did not limit itself to freeways and highways, but also included regional thoroughfares and local city streets. While there was extensive media coverage about the spectacular freeway failures during both the Loma Prieta and Northridge earthquakes, the widespread but less spectacular traffic disruptions caused by these earthquakes are much less widely known.

For the purposes of this report, disruptions to the transportation system were measured in terms of traffic closures to streets and freeways. In order to use these data for modeling future street and freeway closures, the causes, the specific segments closed, and the dates when each segment closed and then opened were determined to the greatest extent possible. In addition, whether or not the closure was the result of a safety concern by public officials or whether it was the result of a right-of-way literally being impassable was also tabulated. A listing of most fields from the database of closures is included as Appendix B.

General Observations

The relative significance of each hazard can be understood in each earthquake and as a whole in terms of how often a certain type of hazard generates a street or freeway closure. As Table 3 shows, the Loma Prieta and Northridge earthquakes were similar in terms of the specific causes of street and freeway closures. The total number of closures as well as the total direct and indirect hazard percentages are close between the two. Moreover, the individual numbers and percentages for specific hazards, such as shaking or landslides, are practically identical. These similarities of transportation disruptions between earthquakes is particularly noteworthy since, in terms of other damage comparisons, the differences are enormous. The number of uninhabitable housing units after the Northridge earthquake, for example, was over 3.5 times greater than those after the Loma Prieta earthquake (Perkins and others, 1996).

While these similarities might suggest that the transportation systems of the San Francisco Bay Area and the greater Los Angeles region have similar vulnerabilities to earthquake damage, there were significant differences in the effects of these earthquakes as explained in the following sections.

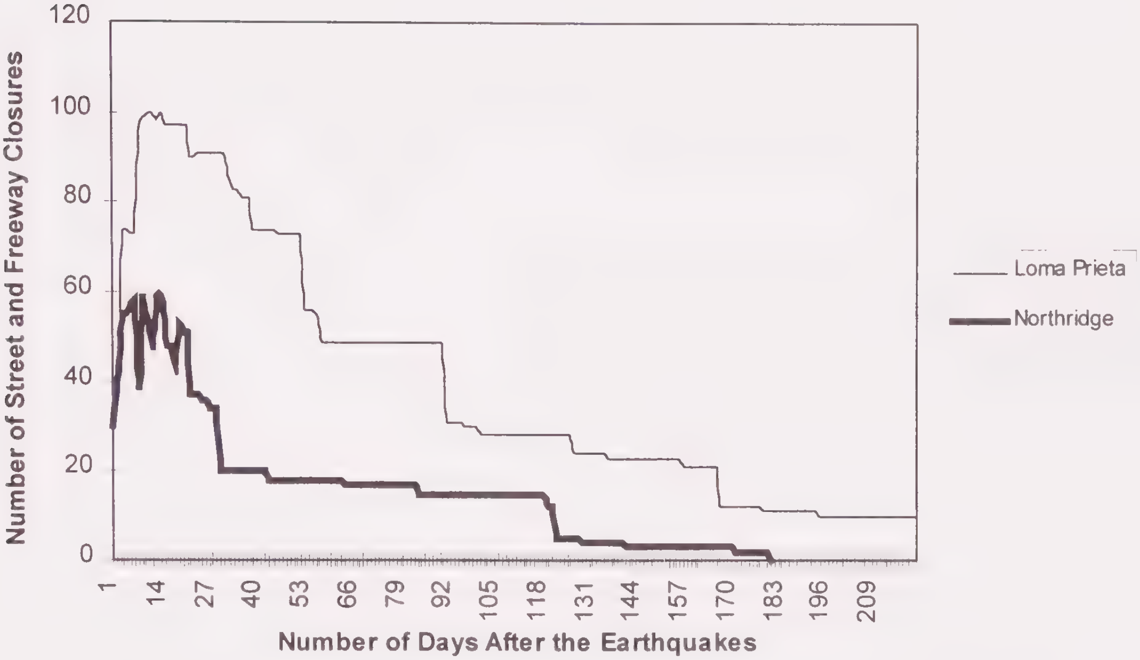
TABLE 3: Summary of Street and Freeway Closures for the Loma Prieta and Northridge Earthquakes[3]

	Hazard Type	Loma Prieta		Northridge		Loma Prieta and Northridge					
		Number	Percent	Number	Percent	Freeways and Highways	Streets	Total	Percent Impas-sible	Average Number Days (All Closures)	Average Number Days (Excludes Some Closures)[4]
	Shaking	30	21%	31	22%	49	12	61	44%	236	58
Direct	Landslides	23	16%	22	16%	16	29	45	53%	22	22
	Liquefaction	17	12%	10	7%	7	20	27	15%	169	64
Hazards	Fault Rupture	0	0%	0	0%	0	0	0	0%	0	0
	Total Direct	**65**	**46%**	**63**	**45%**	**68**	**60**	128	**40%**	**129**	**44**
	Building Damage	43	30%	15	11%	0	58	58	2%	40	40
	Fwy Hazard	15	11%	13	9%	0	28	28	50%	79	79
	Natural Gas Release	0	0%	7	5%	0	7	7	14%	12	12
Indirect	Hazardous Materials Release	0	0%	3	2%	0	3	3	0%	6	6
	Water Main Breaks	17	12%	18	13%	0	35	35	6%	41	41
Hazards	Other	3	2%	13	9%	0	16	16	6%	6	6
	Traffic Control	18	13%	10	7%	10	18	28	0%	35	35
	Total Indirect	**82**	**58%**	77	**55%**	**10**	**149**	**159**	**11%**	**37**	**37**
Public Safety	Public Safety	109	77%	104	74%	42	171	213		50	29
versus	Impassable	33	23%	36	26%	36	33	69		168	90
Impassable	**Total Closures**	**142**	**100%**	**140**	**100%**	**78**	**204**	**282**		79	**40**

[3] When describing freeway closures, there is a distinction between freeway direction, (if it is a north bound or south bound freeway for example), and whether it is an off ramp or an on ramp. Because in most instances damage resulted in closures of these individual freeway components and because the Caltrans reports these data are taken from provide this level of information, each are considered as separate closures making the total number of closures higher. Also important to note is the fact that the percent by hazard do not add up to 100 percent because there may be more than one problem per closure.

[4] This column does not include closures over 500 days in length: the Cypress structures (scheduled for replacement after 3088 days) and Embarcadero freeways (demolished after 805 days), as well as Main Street bridge in Watsonville (rebuilt after 2904 days).

Table 3 indicates that the only significant closure source difference between the Loma Prieta and Northridge earthquakes is building damage, that is, streets which were closed due to building damage. While in the San Francisco Bay Area this hazard type represented 30% of the closures, in the Los Angeles area it only represented 11% of them. This difference can be explained by the significant differences in urban densities that exist between the City of San Francisco where most of these type of closures occurred and the greater Los Angeles area.



Timeline of Street and Freeway Closures
After the Loma Prieta and Northridge Earthquakes
[Note - Several bridge and freeway structures remained closed for over 200 days following the earthquake. See footnote 2 at bottom of previous page.]

While Table 3 indicates that the statistics on causes of closures in the Los Angeles area and San Francisco Bay Area were similar, their effects were significantly different. The timeline above indicates how the number of closures after each earthquake fluctuated. In general, the pattern of closures over time during the first month increases, as public officials barricade areas deemed to be unsafe. At the same time that these officials reopen streets that have been repaired or the hazard has been removed, they close streets to enable more complete repairs or as additional hazards are discovered. While both earthquakes follow this general pattern, there is a significant difference in the magnitude of these increases. The

number of closures after the Loma Prieta earthquake consistently increased until they reached almost 100, ten days after the event and then gradually decreased to about 80 closures. On the other hand, during the first month after the Northridge earthquake, the number of closures fluctuated between 40 and 60 closures after the event. During the first month after the Northridge earthquake, sets of streets that had been closed were opened at the same time that new sets of streets were closed, so that the total number of streets closed never exceeded more than 60 at one time. These differences in the pattern of closures between earthquakes is clearly illustrated by comparing the average number of closure days during each event: 134 days for Loma Prieta versus 22 days for Northridge. In general, after the Northridge earthquake, the process of closing and opening roads occurred at a much faster rate than after the Loma Prieta earthquake. One factor contributing to the speed of recovery following the Northridge earthquake was the public and political support for rapid reconstruction.

Hazard-Specific Information

Direct Hazards versus Indirect Hazards

Combining data for the Loma Prieta and Northridge earthquakes shown in Table 3 leads to several general observations. While there were fewer streets or freeways affected by direct hazards than by indirect hazards, the effects of direct hazards were more severe. While there were 128 total direct hazard closures and 159 indirect hazard closures, 40% of the direct hazard closures resulted in impassable roads versus only 11% of the indirect hazard closures. Similarly, the average number of days a street or freeway was closed was significantly higher for direct hazards.

The data from Loma Prieta and Northridge earthquakes indicate that the impact of direct versus indirect hazards for freeways and streets was significantly different. Freeways were affected by direct hazards almost exclusively, while streets were more frequently affected by indirect hazards (over twice as often as they were affected by direct hazards). Hazards such as shaking, landslides, or liquefaction have been the main hazards affecting freeways. On the other hand, streets have been affected by indirect hazards such as building damage and water main breaks in addition to the direct hazards. However, while freeways have been much less vulnerable to earthquake hazards than streets, almost 50% of the freeway closures have resulted in impassable conditions versus only 16% of the streets.

Direct Hazards

Within direct hazards, shaking-induced structural damage to bridges and overpasses posed the most significant threat for freeways, with 72% of the closures caused by this hazard. While the number of actual freeway failures might seem relatively small, the number of freeway segments which suffered less severe damage but which were closed to traffic was significant. Combining the data from both earthquakes, there were almost 50 freeway segments which were closed due to this type of damage. Freeways segments (such as portions of the new I-980 freeway in Oakland or connectors to I-210 and I-405 in Los Angeles) suffered relatively minor damage when compared to the structures that failed. However, these freeway segments remained closed for several days after the events. In addition, almost 50% of freeways that were closed due to shaking-induced structural damage resulted in impassable conditions.

Source:
David Rodgers, Rodgers/Pacific
Cypress Freeway Collapse
Loma Prieta, Calif. Earthquake of Oct. 17, 1989

Landslides, the next most significant cause of freeway closures, is, at the same time, the most common source of direct hazards to streets. While landslides are a significantly less important source of freeway closures than shaking, the vulnerability of freeways to landslides is a concern. The experience from the Loma Prieta and Northridge earthquakes suggests that landslides are a significant source of concern as seen in the closure of State Route 17 in Santa Clara and Santa Cruz counties, or State Route 1 in Los Angeles. At the same time, landslides affected streets more than any other direct hazard by a factor of almost one third. This hazard is particularly significant in urbanized or semi-urbanized areas with steep topography. Streets within the Santa Cruz mountains (such as Bean Creek Road or Old San Jose Road), or within the Santa Monica mountains (such as Mulholland Drive), resulted in impassable conditions due to landslides.

Indirect Hazards

Indirect hazards are a threat mainly to streets. These hazards often occur simultaneously within severely affected areas such as the Marina District in San Francisco. Many of the streets within the Marina District were affected simultaneously by the indirect hazards of building damage and water main breaks, as well as by the direct hazard of liquefaction. Similarly, in Los Angeles, one of the most famous images after the Northridge earthquakes was that of Balboa Boulevard simultaneously flooded due to a water main break, and on fire, due to a natural gas release.

Obstacles falling on to the street, or their potential of doing so, have been the most significant source of street closures. Both freeway structures and buildings have been a potential source of street closures. These two hazards combined represent over 50% of street closures. Although there were almost twice as many streets closed because of building damage, very few of these (2%) have resulted in impassable conditions. On the other hand, half of the streets closed due to freeway hazard were impassable.

The threat of freeway and building collapses are a source of particular concern within dense urban areas. In the aftermath of an earthquake, freeways within urban areas may become impenetrable barriers in the post disaster setting. In addition to situations such as the collapse of the Cypress freeway in Oakland in which a 10 block strip was closed off, damage to urban freeways often results in ***potential*** collapse, and closure of nearby streets. This situation led to the closure of several streets surrounding the Embarcadero freeway in San Francisco. Similarly, the total or partial collapse of buildings can block streets. While following the Loma Prieta and Northridge earthquakes street closures due to actual collapse of buildings was rare, it was relatively common within the dense and aged urban cores. Over 80% of the streets that were closed due to building damage occurred within the City of San Francisco, which is both high in density and includes many older buildings.

In addition to the hazards described above, there were a number of streets that were closed in order to facilitate traffic flows. While not a hazard in and of itself, the statistics from Loma Prieta and Northridge indicate that, in addition to streets that were closed due to an actual hazard, an additional 18% were closed by public officials in order to facilitate traffic flows.

Likewise, although every effort was made to collect all of the appropriate data, there were a number of streets for which the sources of closures were not known or they were isolated instances. After the Northridge earthquake, for example, a section of Tampa Avenue closed because of a train derailment and a section of Sherman Way closed because of snapped electrical lines. While these situations are extremely unusual, the potential for highly unusual hazards to close roads exists, and needs to be incorporated into modeling for future earthquakes.

Data Collection Procedures

Data on street and freeway closures were collected from the jurisdictions who were involved in closures during the Loma Prieta and Northridge earthquakes. Because earthquakes are emergency situations which require immediate action, most cities focus their resources on dealing with the emergency rather than on keeping accurate records. Data collection focused on trying to combine verbal recollections of the officials involved with available records, resulting in a more complete set of data. In several cases, however, there were no records kept and the only information is from interviews. For the City of San Francisco, for example, the listing of street closures after Loma Prieta does not include any streets within the Marina District; most Marina District streets, according to city officials, were closed. Because these are detailed pieces of information from events that occurred several years ago, there were certain closures which simply could not be explained. The complete closure database is available from ABAG on diskette as a dbf formatted file (ABAG Publication P97ØØ1EQK).

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Housner, George, 1994. ***The Continuing Challenge – The Northridge Earthquake of January 17, 1994***: Report to the Director, California Department of Transportation by the Seismic Advisory Board, George W. Housner, Chairman, C.C. Thiel, Editor. State of California, Department of Transportation, Sacramento, CA, 77 pp.

Perkins, J.B., Chuaqui, B., Harrald, J., and Jeong, D., 1996. ***Shaken Awake! Estimates of Uninhabitable Dwelling Units and Peak Shelter Populations in Future Earthquakes Affecting the San Francisco Bay Area***: Association of Bay Area Governments, Oakland, CA, 143 pp.

Oral and written communications also occurred with the following people regarding closures data from the Loma Prieta and Northridge earthquakes:

- Harvey Quan, San Francisco Dept. of Public Works, Div. of Traffic Engineering, June 1996.
- Chris Gjerde, Los Gatos Dept. of Public Works, June 1996.
- Larry L. Erwin, City of Santa Cruz Dept. of Public Works, July 1996.
- Jack Sohriakoff, County of Santa Cruz Public Works Dept., July 1996.
- Iacote Jeeva, City of Oakland Dept. of Public Works, June 1996.
- Jim Gates, Cynthia MacLeay, Ann Sardo and Mark Yashinsky, California Department of Transportation, Division of Structures, Sacramento, December 1996.

HOW DO WE MODEL TRANSPORTATION SYSTEM DISRUPTIONS IN FUTURE EARTHQUAKES ?

Overview

The process of modeling transportation system disruption in future earthquakes results in a map showing the likelihood of disruption. This map can be used to depict the ***supply*** side of a supply-demand analysis for post-earthquake transportation facilities.

Sources of disruptions are subdivided into ***direct*** and ***indirect*** hazards causing service failure of streets, freeway roadbeds, freeway structures and rail lines. A disruption source is a direct hazard if it is the source of the hazard and it has the capability of ***directly*** causing a transportation-related hazard. Hazards such as ground shaking, liquefaction, landslides, and fault rupture fall within this category. A disruption source will be indirect if it is not the actual hazard source. For example, liquefaction or shaking may cause a pipeline rupture that causes a building to partially collapse, partially blocking a roadway. In another instance, shaking causes a pipeline to break from a tank causing a toxic gas release that, in turn, closes the adjacent roads. Indirect hazards are caused by one or more of the direct hazards.

Sources of disruptions on streets, freeway roadbeds, freeway structures and rail include:

Direct Hazards	Indirect Hazards
Fault Rupture Shaking Damaged Road and Highway Structures Landslides Liquefaction	Building Damage (including associated fires) Water Main Rupture Natural Gas Release (including associated fires) Hazardous Material Release (including associated fires) Dam Inundation Assorted Other Hazards

The disruption factor has been generated using the relationship between the probability of the disruption and the potential severity of that disruption (in terms of extent of disruption and elapsed time for repair) for each combination of disruption source and transportation facilities. While there may be a low probability hazard, its severity of service failure might be high (as in the case of dam inundation which would make 100% of roads out of service) or vice versa.

These two probabilities were obtained by analyzing the data on transportation disruptions from cities during the Loma Prieta, Northridge and possibly Kobe Earthquakes. The actual data from these cities on street and freeway closures were related to the geographic specific data from these earthquakes and their urban contexts so that, given certain conditions, the likelihood of future transportation disruptions can be estimated.

The above relationships can be expressed as:

Disruption Factor = (Probability of Hazard) X (Probability of Road Closure)

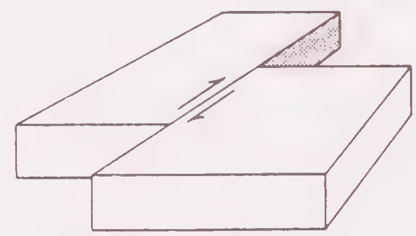
Each of these ten hazards is described on the following pages.

Road Closures Due to Fault Rupture

Background

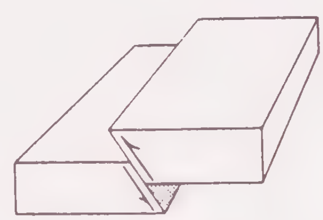
Earthquakes occur in the Bay Area when forces underground cause sudden slip to occur across the faults beneath us. If the rupture extends to the surface, we see displacement on a fault, or surface rupture. But strong earthquakes can occur when the fault rupture does not extend to the surface. ***In both the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake, the fault ruptures did not extend to the surface.*** Because faults are weaknesses in the rock, earthquakes tend to occur again and again on these same Bay Area faults.

Almost all of the major faults in our region are strike-slip faults, where the rupture extends almost vertically into the ground and the ground on one side moves past the ground on the other side of the fault. All of the scenarios being discussed in this report are on these strike-slip faults.



Strike-Slip Fault Diagram

Thrust faults, where ground moves over adjacent ground, are much more common in the Los Angeles area than the Bay Area because the San Andreas fault system makes a large bend to the west there before heading northwest. Many major faults in southern California are associated with this bending.



Thrust Fault Diagram

This analysis is based largely on historical data from earthquakes worldwide of a similar type and structure to those expected in the Bay Area. These data are supplemented by interviews with geologists studying trenches across faults that assess the movement of ancient earthquakes on Bay Area faults.

Assessing the Fault Surface Rupture Hazard by Earthquake Scenario

The following table lists the major strike-slip faults in the Bay Area and the length of the various fault segments expected to rupture in future earthquakes. Given this rupture length, the moment magnitude of the associated earthquakes can be estimated based on a statistical correlation of length versus magnitude worldwide. Once the magnitude is estimated, this value can be used to calculate the expected, or average, horizontal and vertical offsets. In addition, the maximum, or worse case, horizontal and vertical offsets can be estimated. Note that, as stated earlier and as shown in the following table, primary fault rupture did not extend to the surface in the 1989

Loma Prieta earthquake. However, surface displacements associated with shaking or folding did occur in that earthquake. ***All of the values in Table 4 are derived from statistical correlations. It is quite conceivable that the actual values could range from half to double these values.***

TABLE 4: Fault Source Type and Expected Surface Rupture Characteristics for Selected Earthquake Scenarios

[Values in this table are based on statistical correlations as noted in the footnotes. ***Actual values can conceivably range from half to double these values.***]

EARTHQUAKE	Fault Length (in km)	Moment Magnitude[5]	Fault Type	Expected Horizontal Offset (in m)[6]	Expected Vertical Offset (in m)[7]	"Maximum" Horizontal Offset (in m)[8]	"Maximum" Vertical Offset (in m)[9]
Actual Loma Prieta[10]	38.8	6.9	Strike-Slip and Reverse	No primary surface faulting	No primary surface faulting	No primary surface faulting	No primary surface faulting
San Andreas Peninsula	52.4	7.1	Strike-Slip	1.2	0 – 0.4	1.9 – 2.4	0.6
San Gregorio	57.1	7.1	Strike-Slip	1.2	0 – 0.4	1.9 – 2.4	0.6
Northern Hayward	49.3	7.1	Strike-Slip	1.2[11]	0 – 0.4	1.9– 2.4[11]	0.6
Southern Hayward	44.7	7.0	Strike-Slip	1.0[11]	0 – 0.3	1.5– 2.0[11]	0.5
Entire Hayward	85.0	7.3	Strike-Slip	1.8[11]	0 – 0.5	3.1– 3.6[11]	0.9
Healdsburg-Rodgers Creek	56.5	7.1	Strike-Slip	1.2	0 – 0.4	1.9 – 2.4	0.6
Maacama	32.3	6.8	Strike-Slip	0.6	0 – 0.2	1.9 – 2.4	0.3
West Napa	24.1	6.7	Strike-Slip	0.5	0 – 0.1	0.7 – 1.0	0.2
Concord-Green Valley	53.2	7.1	Strike-Slip	1.2[11]	0 – 0.4	1.9[11]– 2.4	0.6
Northern Calaveras	37.2	6.9	Strike-Slip	0.8	0 – 0.2	1.2 – 1.6	0.4
Greenville	53.9	7.1	Strike-Slip	1.2	0 – 0.4	1.9 – 2.4	0.6

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[5] The formula used to estimate moment magnitude for each of these faults segments (from Wells and Coppersmith, 1994) is
Moment Magnitude = 5.16 + [1.12 x log (Surface Fault Length in km)].

[6] The formula used to estimate expected (or average) horizontal offset (from Wells and Coppersmith, 1994) is log (Average Horizontal Displacement, in m) = – 6.32 + (0.90 x Moment Magnitude). ***Actual maximums can range from half to double these values.***

[7] Strike-slip earthquakes in the Bay Area have no significant vertical component over time. This fact was used to create the lower value in the range provided. However, for planning purposes, these values can easily be 30% of the expected horizontal offset (see footnote 5). This calculation is the source of the upper value in the range provided.

[8] The formula used to estimate the lower value in the range of maximum horizontal offset (from Wells and Coppersmith, 1994) is log (Maximum Horizontal Displacement, in m) = – 7.03 + (1.03 x Moment Magnitude). ***Actual maximums can range from half to double these values.*** The upper value in the range provided is double the expected horizontal offset, a value commonly observed but restricted to short sections of the overall rupture length.

[9] The formula used to estimate maximum vertical offset (from Bonilla, 1982) is
Maximum Vertical Displacement = 0.30 x Maximum Horizontal Displacement. ***See the caveats on the following page before using these values.***

[10] Note that surface displacements associated with shaking or folding did occur during the Loma Prieta earthquake.

[11] The active creep which occurs on these faults may act to lower horizontal offsets.

Prediction of Road Closures to Fault Surface Rupture by Earthquake Scenario

The next step is to predict the number of these fault offsets that are likely to result in road closures. This assessment process is difficult in large part due to the relative lack of data on transportation disruptions in recent urban earthquakes. In addition to the lack of surface rupture as a result of the Northridge and Loma Prieta earthquakes, the fault responsible for the 1995 Hyogo-Ken Nanbu earthquake in Kobe, Japan only extended to the surface on the adjacent island of Awaji, not in downtown Kobe.

Even historical earthquakes in the Bay Area are of limited use since accounts of the 1906 earthquake on the San Andreas fault and the 1868 earthquake on the southern Hayward fault are often unreliable, due to the lack of knowledge of faulting at that time by the public, and spotty, due to the low density of the population and the relative lack of roads.

The "classic" surface rupture event in recent California history is the 1992 Landers earthquake in southern California. The horizontal displacement of up to 6.0 meters along a series of faults for 70 kilometers from near Landers northwest through the Mojave Desert. In this case, surface rupture in the Yucca Valley and Landers area disrupted State Highway 247 and local streets. This photograph shows 1 1/2 meters of offset on a road as a result of surface rupture during that earthquake.

Source:
Kerry Sieh, California Institute of Technology
Landers, California Earthquake of June 28, 1992

According to the EERI Special Earthquake Report (August 1992):

> State Highway 247 (Old Woman Springs Road) was disrupted in ten locations. Traffic was not fully restored until eight days later. Other county roads, mostly gravel roads, were similarly disrupted, but remained open to traffic as repairs were conducted.

The 1992 Landers experience, and a review of other major strike-slip earthquakes worldwide, can add several caveats to the numbers in the above table:

- localized conditions may result in vertical offsets in the form of grabens (chasms) several meters deep;
- fault sections in areas of hilly topography are more likely to result in vertical offsets than flat areas because the presence of hillsides implies vertical offset in past earthquakes on either the earthquake's source fault or associated faults;

- local topography can result in apparent vertical offsets of hillside areas, even if no offset on the fault occurred;
- road surface materials (such as concrete, and to a lesser extent, asphalt), tend to buckle and form tent-like structures along fault traces due to localized compression; and
- disruptions of utility lines that cross the fault may result in extreme congestion of repair or response vehicles on narrow roads, even if the roads themselves are not physically impassable.

All of these caveats contribute to transportation disruption regardless of the expected or maximum offset distance.

Based on past experience and given these data, Caltrans and California Highway Patrol (CHP) personnel expect that it is prudent to assume that all of the federal and state highways and county roads crossing these faults would be closed, at least for short periods, for temporary repairs. Such repairs include regrading, creating sand ramps, and installation of warning signs. It is unrealistic to assume that all local roads crossing faults would be immediately checked and repaired, due to the limited resources available after an earthquake. Based on experiences in Loma Prieta and Northridge where local slope failures caused road surface disruption, residents tend to be willing to drive over roads with more disruption than Caltrans and CHP view appropriate. Local roads that are not closed immediately may be partially blocked with cars damaged in their attempts to cross these disruptions. Accordingly, it is reasonable to assume that eventually all local roads crossing ruptured faults will be closed as temporary or permanent repairs are made.

For purposes of calculating the disruption factor discussed earlier, all roads crossing any of these faults are considered closed. The following table summaries the number of these road closures by fault scenario.

Although no significant on-going movement occurred on the surface ruptures following the Landers earthquake, significant creep should be expected on Bay Area faults. This on-going movement will be a maintenance nuisance, rather than a safety or road-closure issue.

Expected Duration of Road Closures Due to Fault Surface Rupture

The expected duration of surface road disruption was from ***0 to 8 days*** in the Landers earthquake. Repair times for landslides, another type of road failure disruption, averaged ***14 days*** in the Loma Prieta and Northridge earthquakes. Thus, these future failures should be anticipated to close roads for several days.

TABLE 5: Prediction of Number of Road Closures Resulting from Fault Surface Rupture for Selected Earthquake Scenarios

[in cases where faults crossed at or adjacent to intersections, this crossing was counted as two closures]

EARTHQUAKE	Predicted Number of Fault-Related Road Closure Incidents			
	Major State and Federal Highways	Thoroughfares	Local Roads	Total Roads
Actual Loma Prieta	0	0	0	0
San Andreas Peninsula	1	2	100	103
San Gregorio	9	0	49	58
Northern Hayward	8	0	274	282
Southern Hayward	8	4	224	236
Entire Hayward[12]	14	4	448	466
Healdsburg-Rodgers Creek	0	3	80	83
Maacama	0	0	22	22
West Napa	1	2	35	38
Concord-Green Valley	9	4	89	102
Northern Calaveras	2	4	75	81
Greenville	0	0	26	26

References

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U. S. Geological Survey, 1992. "Special Issue: The Landers-Big Bear Earthquakes on June 28, 1992" in ***Earthquakes & Volcanoes***: U.S. Geological Survey, v. 23, n. 5, pp. 196-226.

Wells, D.L., and Coppersmith, K.J., 1994. "New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement" *in* ***Bulletin of the Seismological Society of America***, v. 84, no. 4, pp. 974-1002.

Oral communications also occurred with the following people regarding data on Landers and applicable caveats for future Bay Area earthquakes: Manual Bonilla, Kenneth Lajoie, James Leinkaemper, Michael Rymer, David Schwartz and Robert Sharp (U.S. Geological Survey).

[12] Note that the road closures for the Entire Hayward are not the sum of the Northern Hayward and Southern Hayward Scenarios due to some overlap in the predicted ruptures.

Road Closure Due to Ground Shaking-Induced Damage of Street and Highway Structures

Background

The most pervasive problem in earthquakes is the shaking of the ground. However, highway and local street roadbeds are only minimally affected by shaking. It is only when the shaking triggers landslides or liquefaction, or damage to buildings or pipelines which in turn close roads, that these surfaces are impacted. These other earthquake hazards will be described in later sections. Ground shaking can, and has, damaged the bridges and overcrossings on local roads and state highways, however.

Some of our most vivid memories of recent earthquakes involve the spectacular failures of these structures:

- the failure of the I-5 / I-210 Interchange, the I-5 / State Route 14 Interchange, and the San Fernando Road Overhead in the 1971 San Fernando earthquake;
- the failure of the I-880 Cypress Viaduct structure in Oakland, the Struve Slough Bridge on State Route 1 near Watsonville and the I-80/San Francisco-Oakland Bay Bridge in the 1989 Loma Prieta earthquake; and
- the failure of the I-5/State Route 14 interchange, as well as two bridges each on I-10 and State Rd. 118 in the 1994 Northridge earthquake.

Source:
David Rogers, Rogers-Pacific
Struve Slough Bridge, State Route 1
Loma Prieta, California Earthquake of Oct. 17, 1989

These spectacular failures led to an aggressive program being implemented by the California Department of Transportation (Caltrans) to review and strengthen State highway structures. Of the 1,862 structures currently on highways in the 10-county Bay Area (including Santa Cruz County):

- 730 structures have been removed from the Caltrans State Structure Retrofit Program due to year built or structural type (Category 0);
- 300 structures have been retrofitted as of October 1996 (Category 1);
- 589 have been removed from the program as of 1996 based on a screening analysis of the structure by the Caltrans Office of Earthquake Engineering (Category 2);
- 223 have been designated as requiring retrofit, and retrofit has started (effective October 1996) (Category 3); and
- 20 have been designated as requiring retrofit, but retrofit has not started (as of October 1996) (Category 4).

This part of the program does not include structures on local roads as these are being addressed separately in the Caltrans Local Retrofit Program. Statistics on the local retrofit program were

not available at the time of this report. The Caltrans District 4 database used for this project includes 2,131 such local structures within the nine-county Bay Area.

Assessing the Ground Shaking Hazard

ABAG produced a series of maps showing ground shaking hazard in the San Francisco Bay Area based on modified Mercalli intensity for eleven earthquake scenarios on ten faults. The maps were derived from combining (1) a theoretical model which predicts shaking intensity based on average acceleration spectral level (a quantity equivalent to, but not identical to, average spectral velocity) in cm/sec with (2) empirical damage data to homes and apartments (Perkins and Boatwright, 1995).

Because these intensity maps were not specifically developed to predict failures of road structures, it is necessary to determine if the periods of shaking of concern to homes and highway structures are similar, given the obvious differences in size and construction of these two types of structures. The shaking periods of interest to highway structures are based on the height of the columns supporting the structure. For earthquakes of magnitude 7 (such as those being examined in this project, the current model is reasonably valid for periods of less than 1 sec to about 1 sec. This period is sufficient for virtually all highway structures, with the possible exceptions of a few major interchanges. Thus, following a consultation with Caltrans structural engineers, the decision was made to use the existing intensity maps without any attempt to modify them to be accurate for longer periods.

The second step in the process is to estimate the percent of road and highway structures that would not be functional when exposed to each shaking hazard level. In spite of the spectacular failures noted above, ***only 20 of the 1,866 highway structures (1.1 %)*** in the 10-county area affected by Loma Prieta were closed to traffic due to structural damage or collapse from shaking (Housner, 1990, pg. 19; Caltrans, undated PEQIT report; Caltrans Structures and District 4 written communications). All of the 41 structures in the high shaking area (MMI VIII or greater) that had been constructed or retrofitted to current (post-Loma Prieta) Caltrans standards remained functional and in service, although some had minor repairable damage. Because of the way in which the closure information is stored (north vs. south-bound traffic, east vs. west-bound traffic, and post-earthquake closures for repairs and damage assessment), there are ***26 closures*** of highways due to structural damage from shaking in the ABAG database (Appendix B). In addition, ***only one of the 2,131 local bridges*** and overcrossings in the Bay Area (0.05%) were closed,[13] and an additional three local bridges in Santa Cruz County were closed. These local structure closures account for four road closures in the ABAG database (Appendix B).

Similarly, only a very small percentage ***(56 of 2,523, or 2.2%) of the highway bridges*** in Los Angeles County collapsed or became non-functional in the Northridge earthquake (Housner, 1994, pg. 1; Caltrans, undated PEQIT report; Caltrans Structures and District 7 written

[13] This figure is based on oral communications with affected cities. The Housner report (1990, pg. 19) states that 5 local structures were closed, but does not mention the location of these structures. This number does not appear to be correct.

communications; City of Los Angeles Traffic Action Team written communications). Significantly, 5 of the 7 bridges which failed had been designated as requiring retrofit (equivalent to category 4, above). As in the Loma Prieta earthquake, all of the several dozen bridges in the high shaking area that had been constructed or retrofitted to current (post-Loma Prieta) Caltrans standards remained functional and in service, although some had minor repairable damage. Because the ABAG database of closures due to structural damage includes (north vs. south-bound traffic, east vs. west-bound traffic, and post-earthquake closures for repairs and damage assessment), the ABAG database file contains data on ***23 closures***, several of which involved multiple structures. In addition, damage to ***8 local structures*** resulted in the closure of 8 local roads in the ABAG database (Appendix B).

Table 6 shows the ratios of closures versus exposed structures, as well as the percentages used to predict non-functional transportation structures in future earthquakes.

TABLE 6: Percentage of Highway Structures Predicted Non-Functional by Shaking Hazard Level
[followed in parentheses by data (# failures / # bridges exposed) from the ***Loma Prieta*** earthquake]

Shaking Hazard Level	Category 0: Structures Removed from Program due to Year Built or Structural Type	Category 1: Retrofitted Structures	Category 2: Structures Not in Program Based on Screening Analysis	Category 3: Structures in Program, Retrofit Started	Category 4: Structures in Program, Retrofit NOT Started	Local Structures
MMI X	2.5 (0/0)	2.5 (0/0)	25 (0/0)	85 (0/1[14])	85 (0/0)	14 (1/6)
MMI IX	2.0 (0/0)	2.0 (0/0)	20 (0/0)	75 (0/0)	75 (0/0)	11 (0/0)
MMI VIII	1.0 (0/26)	1.0 (0/15)	10 (0/11)	35 (5/15)	35 (1/2)	6 (0/40)
MMI VII	0 (0/288)	0 (0/120)	0 (0/174)	10 (4/74)	10 (4/7)	0 (0/588)
MMI VI	0 (0/196)	0 (0/107)	0 (0/209)	2 (1/87)	2 (1/10)	0 (0/577)
MMI V	0 (0/201)	0 (0/50)	0 (0/152)	1 (0/33)	1 (1/4)	0 (0/920)
Out of Region	- (0/19)	- (0/5)	- (0/40)	- (0/17)	- (2[15]/2)	- (3/unk)
TOTAL	(0 / 730)	(0 / 297)	(0 / 586)	(10 / 228)	(9 / 25)	(1 / 2131) + (3 / unk # for Santa Cruz Co)

Because of the small number of data points, a number of assumptions were made to create this table.

- a larger percentage of structures fail when exposed to higher shaking levels than lower shaking levels;
- a small percentage of removed (category 0) and retrofitted structures (category 1) will not be functional when exposed to high levels of shaking, although that percentage is much smaller than for non-retrofitted structures; these damaged structures are not expected to collapse, and should be repairable;
- those structures removed from the retrofit program due to the screening analysis by the Caltrans Office of Earthquake Engineering (category 2) will be more prone to problems than

[14] This single bridge, the Madrone Drive Undercrossing in Santa Clara County, was damaged, but was not closed.
[15] Struve Slough bridges in Santa Cruz County. Structural problems were caused, in part, by soil liquefaction.

retrofitted structures, but are not nearly as vulnerable to failure as structures with known problems where retrofit has not started or is not completed (categories 3 and 4); and

- local structures[16] tend to be smaller, less complex structures, which are expected to have a closure between that of between retrofitted structures (category 1) and screened structures (category 2).

These assumptions and an analysis of related damage data for non-transportation concrete structures were used to construct Table 6 showing percentages of structures expected to be non-functional by shaking hazard level. ***Note that categories 0 and 1, as well as categories 3 and 4, have been assigned identical percentages.***

Prediction of Bridge and Overcrossing Closures Due to Shaking by Scenario

The next step in the analysis of road and highway structures is to take the table above and apply it to the databases of structures containing information on shaking hazard level for each of the eleven scenarios being examined for this project. Table 7 depicts the results of that analysis.

TABLE 7: Prediction of Non-Functional Structures (Bridges and Overcrossings) for Selected Earthquake Scenarios

[Note: this table was created with October 1996 data on retrofit status. The number of retrofitted structures (category 1) is increasing over time, while those where retrofit has not been completed (categories 3 and 4) is decreasing.]

EARTHQUAKE	Predicted Number of Shaking-Related Non-Functional Structures				
	Categories 0 and 1 - Highways Removed or Retrofitted	Category 2 - Highways Screened Out	Categories 3 and 4 - Highways Where Retrofit Is Not Complete	Local Roads	Total Structures[17]
Actual Loma Prieta (10-county area)	0	0	20	4	24
Actual Loma Prieta (9-county area)	0	0	18	1	19
Predicted Loma Prieta (9-county area)	0	1	18	4	24
San Andreas Peninsula	2	11	27	20	60
San Gregorio	0	2	17	4	24
Northern Hayward	3	21	54	31	109
Southern Hayward	4	29	57	36	126
Entire Hayward	6	40	76	56	177
Healdsburg-Rodgers Creek	2	7	17	17	43
Maacama	0	1	6	2	9
West Napa	0	2	10	6	18
Concord-Green Valley	1	6	18	21	46
Northern Calaveras	2	10	24	13	49
Greenville	0	2	14	6	23

[16] Structures on local roads are not currently included in the Caltrans Structure Retrofit Program database because these are considered to be in a separate program. Therefore, for this analysis and calculations, only the data for state structures have been used.

[17] Total may not be the exact sum of the previous categories due to rounding.

Note that this table is for non-functional structures, not road closures. To obtain road closures, one needs to predict the ratio of road closures to non-functional structures. This ratio was 26 closures / 19 structures for highways in Loma Prieta and 23 closures / 56 structures for Northridge. By combining the two earthquakes, the ratio becomes 49 closures / 75 structures, or roughly 65 percent more closures than non-functional structures. ***Thus, given the variations in these values, as well as the arbitrary nature of the description of these closures, the number of non-functional structures is assumed to be equivalent to the number of road closures in future earthquakes, as shown in Table 8, below.***

TABLE 8: Prediction of Number of Road Closures Resulting from Shaking-Damaged Non-Functional Structures (Bridges and Overcrossings) for Selected Earthquake Scenarios

[Note: this table was created with October 1996 data on retrofit status. The number of retrofitted structures (category 1) is increasing over time, while those where retrofit has not been completed (categories 3 and 4) is decreasing.]

EARTHQUAKE	Predicted Number of Shaking-Related Road Closure Incidents				
	Categories 0 and 1 - Highways Removed or Retrofitted	Category 2 - Highways Screened Out	Categories 3 and 4 - Highways Where Retrofit Is Not Complete	Local Roads	Total Incidents[18]
Actual Loma Prieta (10-county area)	0	0	26	4	30
Actual Loma Prieta (9-county area)	0	0	24	1	25
Predicted Loma Prieta (9-county area)	0	1	18	4	24
San Andreas Peninsula	2	11	27	20	60
San Gregorio	0	2	17	4	24
Northern Hayward	3	21	54	31	109
Southern Hayward	4	29	57	36	126
Entire Hayward	6	40	76	56	177
Healdsburg-Rodgers Creek	2	7	17	17	43
Maacama	0	1	6	2	9
West Napa	0	2	10	6	18
Concord-Green Valley	1	6	18	21	46
Northern Calaveras	2	10	24	13	49
Greenville	0	2	14	6	23

It is important to note that this table was created based on October 1996 data on retrofit status of highway bridges and minimal information on local bridges. As the number of retrofitted structures increases over time, the total number of road closures which might be expected continues to decrease. However, because these structures have been retrofitted to minimize the likelihood of collapse and to prevent fatalities and injuries, they still may be closed for a period of time for repair of any damages.

[18] Total may not be the exact sum of the previous categories due to rounding.

Expected Duration of Bridge and Overcrossing Closures

The expected duration of disruption due to highway structure failures in Loma Prieta and Northridge was from ***less than a day to several years***. The average closure period was 155 days (5 months) if the Cypress, Embarcadero and Watsonville bridges closures of over 500 days are included, and 51 days if those closures are taken out of the database. This source of closure has been the most disruptive, both in terms of length of time and in terms of magnitude of the disruption, of any of the sources of closure.

Damage to retrofitted structures is expected to be less than to non-retrofitted structures. Thus, in future earthquakes, as more structures are retrofitted, the disruption due to extended repairs is expected to be less.

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Perkins, J.B., and Boatwright, J., 1995. ***The San Francisco Bay Area: On SHAKY Ground***: Association of Bay Area Governments, Oakland, CA, 56 pp.

Oral communications also occurred with the following people regarding closures data on Loma Prieta and Northridge and applicable caveats for future Bay Area earthquakes:

- John Boatwright, Geophysicist, U.S. Geological Survey in 1996.
- Jim Gates, Cynthia MacLeay, Ann Sardo and Mark Yashinsky, California Department of Transportation, Division of Structures, Sacramento, California, in December 1996.

Road Closures Due to Earthquake-Triggered Landslides

Background

Landslides are often triggered by the shaking of earthquakes. These ground failures are of two principal types (Keefer, 1984):

- ***disrupted slides and falls*** include landslides with highly jumbled materials that start on steep slopes and at relatively high speeds, such as soil and rock slides, falls and avalanches; and
- ***coherent slides*** include blocks of unjumbled materials that move on a discrete slide surface, such as slumps, block slides and earth flows.

Lateral spreads and flows tend to move like a fluid and are typically associated with liquefaction, so they are discussed in the following section.

Source:
Gerald Wieczorek, U.S. Geological Survey
Livermore, Calif. Earthquakes of Jan. 24-26, 1980

Much effort was made to document the location, shape, and severity of the landslides triggered by the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake. Overall, approximately 1,500 landslides were mapped, and up to 4,000 slides may have occurred, in the Loma Prieta earthquake (Keefer and Manson, in press). However, these 4,000 slides resulted in only *23* road closures. Over 11,000 landslides occurred in the Northridge earthquake (U.S. Geological Survey, 1996). However, in this earthquake, only *22* landslide-related road closures occurred. Significantly, both earthquakes occurred when the ground was exceptionally dry for the time of year.

Assessing the Earthquake-Triggered Landslide Hazard

Extensive research on the distribution and causes of these failures has occurred. The failure rates can be correlated with:

- existing landslide areas;
- shaking strength;
- slope steepness;
- material shear strength (based on geologic material mapping and engineering judgment);
- water saturation (which varies with precipitation and by season); and
- vegetative cover.

The compilation of data on ***existing landslides*** is sporadic at the present time. No regional depository of information exists for the wealth of data collected for individual development projects. Thus, this factor is not incorporated in the hazard mapping which forms the basis of the road closure modeling in this report.

One measure of ***shaking strength*** available for the nine-county Bay Area is the modified Mercalli intensity as developed for the report and maps, ***The San Francisco Bay Area – On Shaky Ground*** (Perkins and Boatwright, 1995). ***In that report, modified Mercalli intensity is correlated with average acceleration spectral level, a quantity equivalent, but not identical, to undamped velocity response spectra.*** That relationship has been modified due to additional data gathered after the Loma Prieta and Northridge earthquakes (oral communication, J. Boatwright, U.S. Geological Survey). ***It has units of velocity, not acceleration.*** Arias intensity is another expression of intensity. It is defined as an integration over time of the acceleration squared (Arias, 1970)[19]. The Arias intensity is also expressed in units of velocity. Several researchers have developed correlations between the earthquake-induced landslide susceptibility and Arias intensity. Because of their similar derivations, average acceleration spectral level and Arias intensity can be compared. These two mathematical intensities, as well as peak velocity, can be correlated with the values on the ABAG intensity maps as shown in the following table (written communication, J. Boatwright, U.S. Geological Survey).

TABLE 9: Approximate Relationships Among Intensity Scales, Particle Velocity and Average Acceleration Spectral Level

Modified Mercalli Intensity (as shown on maps)	Average Acceleration Spectral Level (in cm/sec)[20]	Arias Intensity (in m/sec)	Peak Velocity (in cm/sec)
XII - Extreme Damage with Large Amounts of Ground Failure	(more than shaking related)		
XI - Extreme Damage with Moderately Large Amounts of Ground Failure	(more than shaking related)		
X - Extreme Damage	450	48.7	286
	300	21.6	191
IX - Heavy Damage	204	10.0	130
	141	4.8	90
VIII - Moderate Damage	96	2.2	61
	66	1.1	42
VII - Nonstructural Damage	45	0.5	30
	30	0.2	19
VI - Objects Fall	21	0.1	13
	15	0.05	10
V - Pictures Move	9	0.02	6

Researchers have correlated areas of known earthquake-induced landslides to Arias intensity. Areas subject to Arias intensities of greater than about 0.54 m/sec commonly have earthquake-

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[19] The actual formula is $I_{\partial} = \frac{\pi}{2g}\int_0^{\infty}[a(t)]^2\,dt)$, where I_{α} is Arias intensity, g is the acceleration of gravity, and the remaining term is the integration of acceleration over time.

[20] ***Average acceleration spectral level is a quantity equivalent, but not identical, to undamped velocity response spectra.*** That relationship has been modified due to additional data gathered after the Loma Prieta and Northridge earthquakes (oral communication, J. Boatwright, U.S. Geological Survey). ***It has units of velocity, not acceleration.***

triggered landslides. As shown in the table above, this intensity is roughly equivalent to a modified Mercalli intensity of VII or greater. (Although the cutoff is not exact, it was not believed that the accuracy of either the maps or the landslide/intensity data warranted the effort needed to subdivide the MMI units further.) Small numbers of landslides can occur at longer distances, roughly equivalent to MMI VI.

To generate a regionwide map of earthquake-induced landslide potential it is also necessary to have a regionwide digital file of ***slope steepness***. Slope length and slope aspect (that is, orientation facing north, south or somewhere in between) are other potential contributors to earthquake-induced landslide susceptibility. However, slope steepness (as expressed in percent slope) is the predominant factor. The U.S. Geological Survey has developed Digital Elevation Model (DEM) coverage of most of the Bay Area on a 30-meter grid resolution. Although 10 meter resolution would be much more accurate and has been made available to researchers working in part of the Los Angeles basin analyzing data from the Northridge earthquake, the 30-meter coverage is the best currently available for the Bay Area.

A third factor required in generating this map is ***material shear strength***. ABAG currently has a map of geologic materials used to generate the shaking intensity map. This same mapping can be used. However, it is also necessary to develop a correspondence table between geologic materials and shear strength. Because of the lack of measurable data, this table was generated using "engineering judgment" with the assistance of David Keefer, a researcher specializing in earthquake-induced landsliding at the U.S. Geological Survey and tables from a map of earthquake-induced landslide susceptibiltiy in San Mateo County (Weiczorek and others, 1985). The resulting table is included as Appendix C, which shows the geologic units in the Bay Area and the equivalent material shear strength classification of A, B, or C, with A being those units least susceptible to sliding and C being those units most susceptible to sliding.

The next factor required for this map is degree of ***water saturation***. This variable depends in large part on length of time since the last major storm and rainfall to date. Because these data cannot be known ahead of time, this factor was estimated using the assumption that saturation would be present for roughly one-fourth of the year.

The final factor contributing to earthquake-induced slope stability is ***vegetative cover***. However, very little research has been conducted quantifying this factor. Thus, vegetative cover is not a part of the model of earthquake-induced landslides used for this project.

The following two tables show the combinations of intensity, slope, and materials used to predict earthquake-induced landslide potential for the Bay Area. Because of the dependence of landslide potential on shaking intensity, the tables have separate values for each intensity. However, the intensities required for landslides tend to be lowered by approximately one intensity unit under wet (winter) conditions. Thus, a second table has been presented to indicate the needed changes.

TABLE 10: Earthquake-Induced Landslide Susceptibility – Dry (Summer) Conditions – Based on Intensity, Slope, and Material and Expressed as a Percentage of the Land Units Being Analyzed Expected to Have at Least One Landslide [where these land units are one hectare squares, or units 100 meters on each side]

Modified Mercalli Intensity	Material Type	0 - 5 % Slope	6 - 15 % Slope	16 - 30 % Slope	30+ % Slope
	A	0	1	5	8
IX and X	B	1	2	8	18
	C	2	12	18	30
	A	0	0	0	5
VIII	B	0	0	5	8
	C	0	5	12	18
	A	0	0	0	3
VII	B	0	0	3	5
	C	0	3	4	12
	A	0	0	0	0
VI	B	0	0	0	0
	C	0	0	0	0

TABLE 11: Earthquake-Induced Landslide Susceptibility – Wet (Winter) Conditions – Based on Intensity, Slope, and Material and Expressed as a Percentage of the Land Units Being Analyzed Expected to Have at Least One Landslide [where these land units are one hectare squares, or units 100 meters on each side]

Modified Mercalli Intensity	Material Type	0 - 5 % Slope	6 - 15 % Slope	16 - 30 % Slope	30+ % Slope
	A	1	5	8	12
IX and X	B	2	8	18	24
	C	12	18	30	50
	A	0	1	5	8
VIII	B	1	2	8	18
	C	2	12	18	30
	A	0	0	0	5
VII	B	0	0	5	8
	C	0	5	12	18
	A	0	0	0	3
VI	B	0	0	3	5
	C	0	3	4	12

Correlating Earthquake-Induced Landslide Hazard and Road Closures

The next step is to calculate the number of road closures resulting from landslide potential. Obviously, there are significant problems in assuming that only a fixed percentage of potential slide areas will result in road closures. The principal problem with such an assumption is that much of the steep area exposed to the highest shaking intensities in those two earthquakes was

relatively undeveloped. This will not be the case in some of the future earthquake scenarios being considered, particularly those involving the Hayward fault. Thus, it is essential that the kilometers of road ***exposed to sliding*** be determined in the landslide-prone areas. Using the street network available from the U.S. Bureau of the Census (the Tiger files), the number of kilometers exposed to landslides was calculated. Then, as the final factor added to this model, an estimate of the kilometers of highways and streets which needs to be exposed to a landslide hazard before a road closure occurs was added. No previous research on this value was located.

However, since reliable statistics on road disruption from landslides are also available for both the Loma Prieta and Northridge earthquakes, the overall landslide statistics cited above can also be used to correlate estimates of landslide nazard in future Bay Area earthquakes with road disruption. This value was generated by producing a landslide susceptibility map for the Loma Prieta earthquake and using that map to determine the number of closures per kilometer of landslide hazard exposure. This value was determined to be ***0.08*** closures per kilometer.

Prediction of Road Closures Due to Landslides by Earthquake Scenario

Applying the model described above to the eleven future earthquakes being studied as part of this project yields the results in the following table.

TABLE 12: Prediction of Number of Road Closures Resulting from Earthquake-Induced Landslides for Selected Earthquake Scenarios

EARTHQUAKE	Predicted Number of Landslide-Related Road Closure Incidents	
	Dry Conditions	Wet Conditions
Actual Loma Prieta (10-county area)	23	not applicable
Actual Loma Prieta (9-county area)	7	not applicable
Modeled Loma Prieta (9-county area)	7	24
San Andreas Peninsula	14	41
San Gregorio	6	23
Northern Hayward	20	65
Southern Hayward	15	58
Entire Hayward	29	101
Healdsburg-Rodgers Creek	8	43
Maacama	3	12
West Napa	4	20
Concord-Green Valley	9	38
Northern Calaveras	9	32
Greenville	3	18

Note that the "dry weather" values are normalized against data from an exceptionally dry October, an exceptionally dry value. Therefore, the overall model uses the values for "wet weather" conditions. These values may also be too low when soils are completely saturated.

Expected Duration of Road Closures Due to Earthquake-Triggered Landslides

As stated earlier, repair times for roads closed by landslides averaged ***14 days*** in the Loma Prieta and Northridge earthquakes. Thus, these future failures should be anticipated to close roads for several days to a few weeks.

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Written and oral communications also occurred with the following people landslide statistics and applicable modeling for future Bay Area earthquakes: David Keefer, Randy Jibson and Jack Boatwright (U.S. Geological Survey).

Road Closures Due to Liquefaction

Background

Liquefaction is a process by which sandy, water-saturated materials lose shear strength when shaken during an earthquake. Liquefaction is defined as "the transformation of a granular material from a solid state into a liquefied state as a consequence of increased pore-water pressure" (Youd, 1973, p. 1). In the process, ground displacement, ground failure and lateral spreads and flows can occur.

The liquefaction hazard from a given earthquake scenario is based on:
- the geologic material;
- ground water table (which indicates likelihood that those materials are saturated; and
- shaking severity.

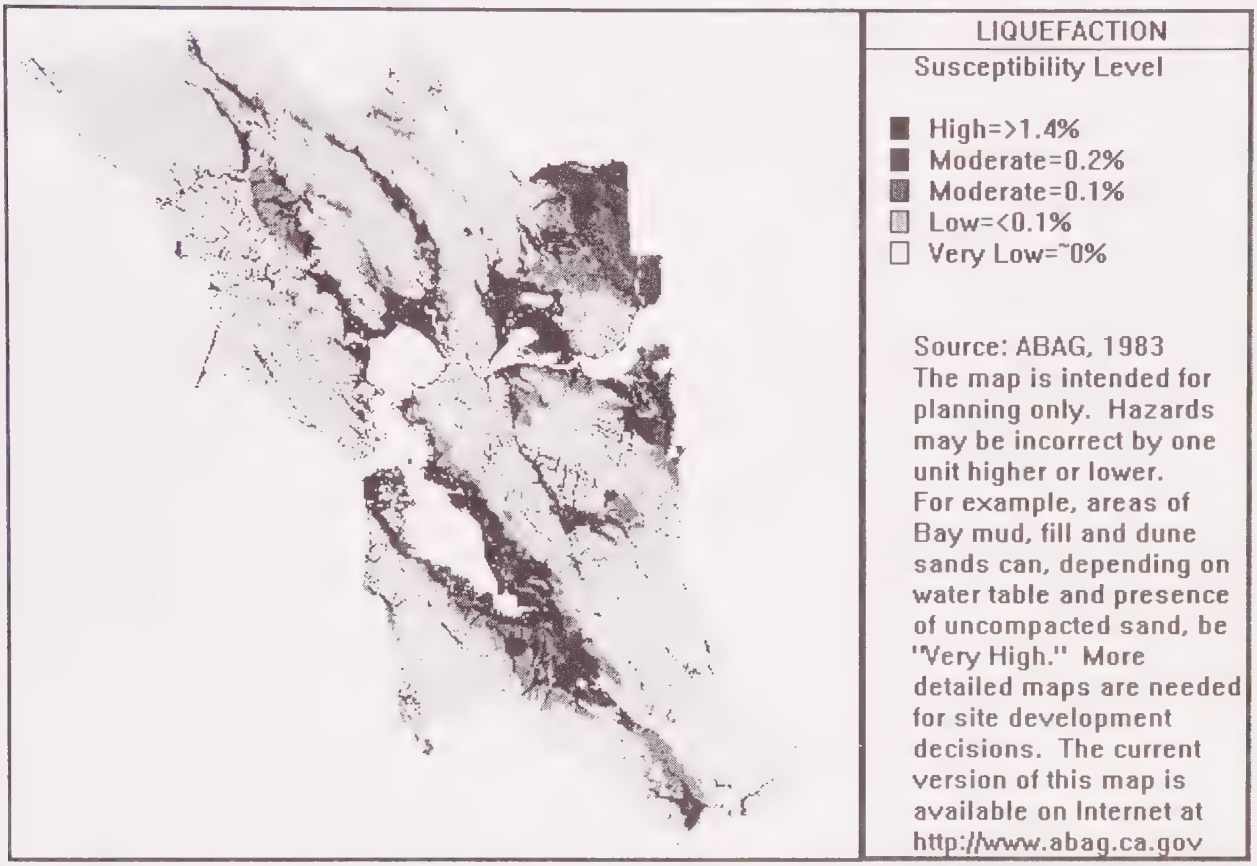
As with landsliding, an effort was made to review the literature to document the location and severity of the liquefaction and ground failure triggered by the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake. Overall, liquefaction was not nearly as well documented as landsliding. Liquefaction and associated settlement or other ground failure were responsible for only ***17*** instances of road closure following the Loma Prieta earthquake and only ***10*** instances of road closure following the Northridge earthquake.

Source:
M. Bonilla, U.S. Geological Survey
Lateral Spread-Induced Road Failure, Lake Merced
Daly City, Calif. Earthquake of March 22, 1957

Assessing the Liquefaction Hazard

ABAG and William Lettis and Associates are in the process of updating the liquefaction susceptibility mapping for the Bay Area with funding from the U.S. Geological Survey. Unfortunately, this mapping is not completed and therefore cannot be incorporated into this transportation analysis. Therefore, this report makes use of liquefaction susceptibility maps ABAG developed in 1980/83/87. These outdated maps are the only "complete" and "consistent" mapping of the liquefaction hazard in the Bay Area. The maps estimate the susceptibility of various geologic materials to liquefaction based on the type of material and a rough approximation of ground water levels. The principal problem with the maps is that those portions of Bay mud, stream deposits and saturated dune sands that, using today's techniques, are known to have a "very high" susceptibility to liquefaction are indicated on this map as "high," while other areas which should be shown as "moderately high" or "high" are shown as "very high." The maps also do not make direct use of ground water table information (which is needed to estimate whether or not the water saturation is present for liquefaction to occur).

As a partial improvement of these files, the 1:100,000 map of the San Francisco sheet, which has been completed though not published (Knudsen and others, in press), was examined. A correspondence table between the hazard levels associated with each combination of "old" and "new" susceptibility category was generated. Based on this assessment, the units with a susceptibility of "High" or greater on the ABAG mapping (Perkins, 1993; Youd and Perkins, 1987) were viewed as being susceptible to liquefaction for purposes of this project. The "revised" liquefaction susceptibility for each of the geologic materials in the Bay Area is provided in Appendix C.



These maps do not incorporate shaking severity information which is needed to create an actual liquefaction potential hazard map. Although techniques to improve the way such a map is generated will be developed as part of the Lettis/ABAG/USGS work described above, some assumptions were made to create a general estimation of hazard level for this transportation project. Shaking strength needed for liquefaction was estimated by Burke and others (1979) as $M = 5 + 1.5 \log D$, with M = magnitude and D = critical distance from the fault for liquefaction, in km, and with 150 km as a maximum. For a M = 7.3 event (the entire Hayward), the critical distance from this 1979 formula is approximately 100 km, while for a M = 6.7 event (the West Napa), the critical distance is only 30 km. The Loma Prieta earthquake, with a M = 6.9, would have had a critical distance of 45 km. Liquefaction which occurred in the Marina District of San Francisco, as well as near the Oakland Airport, far exceeded this distance (probably due to

directivity and the Moho "bounce" as described in Perkins and Boatwright, 1995). Given the inconsistencies of this formula with the data from Loma Prieta, as well as with shaking mapping being used for this project (from Perkins and Boatwright, 1995), this 1979 formula was not used. Instead, an attempt was made to develop a simple conversion to the approximate equivalent intensity level. Modified Mercalli intensity (for shaking) of VIII or greater was estimated as being required for liquefaction.

Correlating Liquefaction Hazard and Road Closures

The next step was to take the number of road closures due to liquefaction and divide this value by the areas viewed as having both "High" liquefaction susceptibility and exposures to intensity VIII or greater. Approximately ***328*** kilometers of roads and highways were exposed in the Loma Prieta earthquake, and, as stated earlier, only ***17*** closures (of which only ***14*** were in the Bay Area) occurred, for a rate of approximately ***0.043*** closures per kilometer of Bay Area road in liquefaction hazard areas.

Prediction of Road Closures Due to Liquefaction by Earthquake Scenario

Applying the model described above to the eleven future earthquakes being studied as part of this project yields the results in the following table.

TABLE 13: Prediction of Number of Road Closures Resulting from Liquefaction for Selected Earthquake Scenarios

EARTHQUAKE	Predicted Length (in km) of Bay Area Highways and Roads Exposed to Liquefaction Hazard	Predicted Number of Liquefaction-Related Road Closure Incidents
Actual Loma Prieta (9-county area)		14
Predicted Loma Prieta (9-county area)	328	14
San Andreas Peninsula	658	28
San Gregorio	464	20
Northern Hayward	954	41
Southern Hayward	934	40
Entire Hayward	1025	44
Healdsburg-Rodgers Creek	890	38
Maacama	20	1
West Napa	229	10
Concord-Green Valley	557	24
Northern Calaveras	476	20
Greenville	181	8

Expected Duration of Road Closures Due to Liquefaction

As stated earlier, repair times for roads closed by liquefaction averaged ***169 days*** in the Loma Prieta and Northridge earthquakes, in part due to the expected closure of the Main Street bridge in Watsonville for approximately *8 years* (2904 days). If this single closure is ignored, the

average closure is ***64 days***. Thus, these future failures should be anticipated to close roads for ***two months*** to a ***few years.***

References

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Road Closures Due to Building Damage

Background

Roads are closed in earthquakes due to building damage either because of collapse of a structure or, more typically, concern of imminent collapse. Earthquake shaking can result in the collapse of a building and literally block an adjacent road. At the same time, earthquake shaking can damage a building so severely that building officials close adjacent roads for public safety reasons. This latter type of closure is by far more common: the combined statistics from Loma Prieta and Northridge indicate that almost 98% of the roads that were closed due to building damage were closed by local officials for public safety reasons.

Closures due to building damage are a significant source of street disruptions, particularly in high density areas. However, the public's perception of the potentially disruptive effect of buildings on roads is lessened because building damage is generally not as spectacular or well publicized as other sources of disruption. During the Loma Prieta earthquake, for example, 30% of all the street closures were due to building damage while only 11% were closed because of freeway hazard. During the Northridge earthquake which impacted an area of significantly lower urban density than the San Francisco Bay Area, 11% of the road closures were attributed to building damage, while 9% were closed due to freeway hazard. Numbers such as these indicate that the effects of damaged buildings to the street network should be a significant source of concern.

Source:
C. Meyer, U.S. Geological Survey
Building in Marina District, San Francisco
Loma Prieta, Calif. Earthquake of October 17, 1989

Methodology for Assessing the Building Damage Hazard

Road closures due to building damage following the Loma Prieta and Northridge earthquakes were, without exception, generated by buildings which were red-tagged, that is, buildings which were so heavily damaged that they were deemed unsafe by local building inspectors. Data on the number and location of red-tagged buildings following both the Loma Prieta and Northridge earthquakes were collected by the local jurisdictions. These city and county building departments made their data available to ABAG. ABAG checked the location and construction type information to ensure its consistency.

Because road closures due to building damage are generated by red-tagged buildings, the total number of this type of street disruption can be understood as a percentage of the total number of red-tagged buildings. At the same time, in the Loma Prieta and Northridge earthquakes, it often took several buildings to close one street. Thus, the ratio between buildings and closed streets is often not one-to-one, and, accordingly, the percentage described above is adjusted by a ratio of closed streets to red-tagged buildings. The chart below broadly illustrates this process:

Number of Red-Tagged Buildings	**X**	**Fraction of Red-Tagged Buildings Involved in Street Closures**	**X**	**Ratio of Closed Streets to Buildings Involved in Closures**	**=**	**Number of Closures**

Building Damage Closures During the Loma Prieta and Northridge Earthquakes

For the purposes of analyzing building damage related closures, an understanding of the types of buildings involved in closures during past earthquakes was necessary. Because of differences in construction, configuration and square footage, a distinction was made between residential and commercial buildings. Residential buildings were classified according to the method used in the ABAG report on housing losses in earthquakes (Perkins and others, 1996). An analysis of the residential buildings responsible for closures in these earthquakes revealed that of the 13 residential building types described by Perkins and others (1996), six residential types involving a total of 120 buildings were involved in the 29 of the 58 road closures due to building. While commercial buildings generated an equal number of closures, only 44 commercial buildings were involved in closures and 37 of these were of unreinforced masonry (URM) construction.

Because only seven commercial buildings that were not URMs were involved in road closures during the Loma Prieta and Northridge earthquakes, a more limited analysis was conducted on the commercial inventory. These seven commercial non-URM buildings proved to be various types of concrete structures: a six story medical office building, a four story parking garage, and several mid-rise office buildings. While these seven concrete buildings represent but a small percentage of the total structures involved closures, the evidence from Loma Prieta and Northridge indicates that statistically it one building can close more than one adjacent road.

Table 14 below illustrates the data collected for this analysis. As the last two columns of this table indicate ("Percent of Red-Tagged Buildings Involved in Closures" and "Ratio of buildings per closure"), certain building types have the potential to generate a greater or lesser number of road closures. In other words, it might take more or less of a certain building type to close a road. Although the table suggests that 52% of red-tagged buildings which were built prior to 1940 between four and seven stories and wood (Type 7) were involved in road closures, it actually took almost six of these damaged buildings to close each road. On the other hand, while only 2% of miscellaneous commercial buildings red-tagged were involved in road closures, it only took two of these buildings to close three adjacent roads. Because of discrepancies such as these on the effect of different building types over roadways, the percent of red-tagged buildings involved in road closures is adjusted by a ratio that accounts for these discrepancies.

TABLE 14: Building Types Generating Road Closures During the Loma Prieta and Northridge Earthquakes
[Source: ABAG survey of jurisdictions involved in Loma Prieta and Northridge earthquakes. The data from the Loma Prieta earthquake used in the table does not include data from Santa Cruz County because the overall building stock data were not available for that county.]

Residential Type		Total Buildings Involved in Closures	Total Streets Closed	Number of Red-Tagged Buildings	Percent of Red-Tagged Buildings Involved in Closures	Ratio of Buildings per Closed Street
Type 2	URM Residential	3	3	64	5%	1.00
Type 3	Non-Wood 4-7 pre 40	1	1	9	11%	1.00
Type 7	Wood 4-7 stories pre 1940	29	5	56	52%	5.80
Type 9	Wood 1-3 stories pre 1940	49	14	293	17%	3.50
Type 10	Wood 1-3 stories post 1939	20	3	310	6%	6.67
Type 11	Single Family pre 1940	16	2	623	3%	8.00
Commercial Type						
URM Commercial		23	15	166	14%	1.53
Miscellaneous Commercial Buildings		7	10	358	2%	0.70
Total		**148**	**53**	**1879**	**8%**	**2.79**

Estimating Future Road Closures due to Building Damage

The first step to predict the number of road closures due to building damage is to estimate the number of red tagged buildings in future earthquakes for each of the three different building categories: (1) residential, (2) commercial URMs, and (3) commercial concrete buildings.

1) For the residential building stock, this analysis was already done by ABAG (Perkins and others, 1996). This report estimates the number of uninhabitable dwelling units by building category, and all that was necessary was an equivalency table to transform the number of units into number of buildings.

2) A similar calculation was done for the commercial URM buildings. Since these have identical characteristics as the residential URMs and ABAG has an inventory of all the commercial URM buildings in the Bay Area, the number of future red-tagged commercial URMs was calculated by using a damage matrix identical to that used for red-tagged residential URMs.

3) The process for estimating future red-tagged commercial concrete buildings in future earthquakes is slightly more complex since little data are readily available. While there are various studies which calculate a percent red-tagged by earthquake intensity (see, for

example, EQE International and California Governor's Office of Emergency Services, 1995, for the Northridge earthquake), an inventory of these buildings is required in order to generate a number of commercial concrete buildings. Because no inventory exists this calculation was based on two techniques.

- IF the ABAG building construction survey conducted in 1985 had an actual number of concrete buildings for a particular census tract for commercial and industrial uses, that number was used directly.
- IF that ABAG survey only contained information on the PERCENT of commercial and industrial buildings which were concrete, then that percentage was applied to the number of parcels by non-residential land use by census tract obtained from the nine county assessors offices.

Although this analysis assumes one building per parcel and it combines data from 1985 and 1997, it nonetheless provides an inventory of commercial concrete buildings which seems to be within the correct order of magnitude.

TABLE 15: Percent of Dwelling Units/Buildings Red Tagged by Construction Type and MMI Intensity

	INTENSITY					
RESIDENTIAL TYPE[21]	V	VI	VII	VIII	IX	X+
Unreinforced Masonry	0	0.05	2.9	45	70	80
Non-Wood , 4-7 Stories, <1940	0	0.30	8.0	45	70	80
Wood-Frame, 4-7 Stories, <1940, Multi-Family	0	1.4	2.5	45	70	80
Wood-Frame, 1-3 Stories, <1940, Multi-Family	0	0.05	0.53	11	44	64
Wood-Frame, 1-3 Stories, >1939, Multi-Family	0	0.01	0.04	6.5	15	25
Wood-Frame, 1-3 Stories, <1940, Single Family	0.01	0.04	0.12	1.8	8.4	12
Wood-Frame, 1-3 Stories, >1939, Single Family	0	0	0.02	0.18	0.69	1.8
COMMERCIAL TYPE						
Unreinforced Masonry[22]	0	1.0	8.0	45	70	80
Miscellaneous Concrete[23] Commercial Buildings	0	0	1.0	20	33	40

[21] The residential building types relating intensity and constructions type are taken from ***Shaken Awake!*** (Perkins and others, 1996, pg. 68).

[22] Note that the commercial unreinforced masonry values are higher than those for the residential unreinforced masonry.

[23] Taken from ***The Northridge Earthquake of January 17, 1994: Preliminary Report of Data Collection and Analysis***, (EQE and OES, 1995, Table 4-3), except for MMI VII (which was revised downward from 8% to 1%

The accuracy of this methodology can be gauged by comparing the actual number of road closures during the Loma Prieta earthquake with the calculated predicted number. Table 16 shows the result of this comparison.

TABLE 16: Predicted Versus Actual Road Closures During the Loma Prieta Earthquake

Residential Buildings		Actual Loma Prieta Total Number of Red-Tagged Res. Units or Comm. Bldgs.	Bay Area Housing Unit Averages[24]	Predicted Number of Red Tagged Buildings[25]	Fraction of Red Tagged Buildings Involved in Closures[26]	Predicted No, of Buildings Involved in Closures	Average Number Closures per Building	Predicted Number of Closures	Actual Number of Closures
Type 2	URM Residential	587	25	23	0.167	4	1	4	3
Type 3	Non-Wood 4-7 stories pre-1940	720	69	10	0.111	1	1	1	1
Type 7	Wood 4-7 stories pre-1940	815	25	33	0.518	17	0.17	3	5
Type 9	Wood 1-3 stories pre-1940	877	7	130	0.167	22	0.29	6	9
Type 10	Wood 1-3 stories post-1939	59	43	1	0.065	0	0.2	0	1
Type 11	Single Family pre-1940	301	1	301	0.026	8	0.13	1	2
Total Residential		3359	170	499		52		15	21
Commercial Buildings									
URM Commercial		66			0.348	23	0.65	15	15
Miscellaneous Commercial Buildings		114			0.020	2	1.57	4	2
Total Commercial		180						12	17
Total								28	38

As the above table shows, the ABAG estimate is lower than the actual number of closures. Overall there is a discrepancy of 25% which is consistent with the discrepancy of the total residential and the total commercial buildings.

Analysis of Building Damage Related Closures by Scenario

The final step in the analysis of building damage related closures is to take the above methodology and apply it to the databases generating red-tagged buildings for each of the eleven Bay Area scenarios, generating the table below.

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based on lack of damage in the Loma Prieta earthquake). These percentages apply to all types of concrete buildings.

[24] Average number of units in the nine-county Bay Area for all building types (except for building types 9 and 10 which also include data from Los Angeles because Bay Area data is limited and incomplete).

[25] Commercial buildings consist of the actual number of red-tagged buildings during Loma Prieta.

[26] Data from Loma Prieta and Northridge earthquakes, except for both residential and commercial URMs which includes Loma Prieta data only. Northridge data was not included due to the distortions created from the extensive retrofit programs required by the City of Los Angeles in which large numbers of URMs have been strengthened to withstand collapse. This program is not as extensive in the Bay Area.

TABLE 17: Predicted Number of Bay Area Road Closures due to Building Damage for Selected Earthquake Scenarios

EARTHQUAKE	Predicted Number of Building-Related Road Closure Incidents
Actual Loma Prieta (10-county area)	43
Actual Loma Prieta (9-county area)	38
Predicted Loma Prieta (9-county area, based on *Predicted,* not actual, red-tagged buildings)	34
San Andreas Peninsula	72
San Gregorio	36
Northern Hayward	160
Southern Hayward	109
Entire Hayward	300
Healdsburg-Rodgers Creek	45
Maacama	5
West Napa	12
Concord-Green Valley	23
Northern Calaveras	16
Greenville	8

Expected Duration of Road Closures Due to Building Damage

It is difficult to know of precisely how long roads will have to remain closed after a water main rupture. However, based on data from the Northridge and Loma Prieta earthquakes, closure time averaged ***40*** days or roughly 1 1/2 months! The data from the Marina District were complicated by the existence of multiple problems in the same area. Thus, in some of the smaller scenario earthquakes, this estimate is probably high. However, the three Hayward events may produce interrelated damage patterns in large areas of Bay mud and along the fault in the East Bay hills.

References

EQE International and the Geographic Information Systems Group of the Governor's Office of Emergency Services, 1995. ***The Northridge Earthquake of January 17, 1994: Preliminary Report of Data Collection and Analysis -- Part A: Damage and Inventory Data***: Governor's Office of Emergency Services of the State of California: Sacramento.

Perkins, J.B., Chuaqui, B., Harrald, J., and Jeong, D., 1996. ***Shaken Awake! Estimates of Uninhabitable Dwelling Units and Peak Shelter Populations in Future Earthquakes Affecting the San Francisco Bay Region***: ABAG, Oakland, CA, 142 pp.

Road Closures Due to Water Pipeline Ruptures

Background

Water pipelines rupture in earthquakes, either due to the shaking itself (that is, strain and curvature of the ground due to the traveling waves) or permanent ground deformation (from landslides, liquefaction, differential settlement, or fault rupture). A small percentage of these ruptures are in a location and of a size that the adjoining roadway is closed. The purpose of the modeling being described in this section is to predict the location of water pipeline ruptures and associated road closures. ***The emphasis of this model is on the prediction of ruptures due to shaking, rather than ground deformation. The assumption is that landslides, liquefaction and fault rupture will have closed the roads directly, without the need to model water pipeline ruptures.***

This hazard is not as significant as some other hazards that close roads, but it is also not insignificant. ***In the Loma Prieta earthquake, there were 1,200 pipeline repairs, of which 17 closed roads. In the Northridge earthquake, there were 1,700 pipeline repairs, of which 18 closed roads.***

Note that these statistics are for pipeline repairs, not pipeline breaks. This subtle distinction is a real issue. Not all breaks that may occur are discovered if they are not accompanied by detectable leaks. Also, not all breaks that ***are*** detected are always due to the seismic event; a pre-existing break that had not produced significant leakage may be discovered once a damaged segment of pipe is exposed.

Source:
East Bay Municipal Utility District Slide Collection
Water Main Rupture
Northridge, California Earthquake of Jan. 17, 1994

Assessing the Water Pipeline Rupture Hazard

The two variables most directly related to the water pipeline performance in earthquakes are:

- shaking severity; and
- pipeline type, including material, type of joint, size and age.

The water pipeline rupture hazard has been the topic of several research reports. The most easily adapted to a model for use in this project is work by Eguchi (1991) and O'Rourke and Ayala (1993) in which data from recent earthquakes are used to correlate ***damage repair rates*** (in

repairs per kilometer of pipe) versus ***shaking*** (expressed as peak ground velocity or modified Mercalli intensity). Following several model tests relating these data to actual statistics from the Loma Prieta earthquake, the relationships of Eguchi (1991) were found to more closely correlate with Loma Prieta data than those of O'Rourke and Ayala (1993).

The choice of which Eguchi (1991) damage/shaking severity curve to use depends on knowledge of the type of ***pipeline material*** in the region. As a result of the dozens of water supply agencies in the region independently installing water pipelines and mains, a huge variety exists in the materials used for pipelines. Newer lines are generally composed of steel, ductile iron, or polyvinyl chloride (PVC), while older pipes may be cast iron, with cement or lead-caulked joints, or riveted steel pipe. A newer type of pipe, such as that used to replace lines in the Marina, is ductile iron pipe with rubber gasket joints. The largest are usually made with pre-stressed concrete. Steel and asbestos cement pipes are also common, usually in intermediate sizes and manufactured in the 1960s and 1970s. Customer service connections may be galvanized iron, copper, or PVC. Lines most vulnerable are brittle pipes and those affected by corrosion. Since corrosion can be a problem, acidic soils are particularly poor candidates for cast iron and steel lines, and in unstable soils due to liquefaction. The following table shows the six-fold variation in repair rates for different pipeline materials experienced by EBMUD following the Loma Prieta earthquake.

TABLE 18: Actual Water Pipeline Repairs to EBMUD's Pipe Distribution System Due to Both Shaking and Ground Failure in the 1989 Loma Prieta Earthquake (EBMUD, 1994, pg. 234)

Material	Number Repairs	Repair Rate	
		per 1000 feet of pipe	per kilometer
Cast Iron	52	0.007	0.023
Steel	46	0.012	0.039
Asbestos Cement	13	0.002	0.007
PVC	2	0.002	0.007
Service Connections	22	–	–
TOTAL	135		

However, data are not readily available on the location of these pipeline materials in the Bay Area suitable for incorporation into the model being used for this project. Due to this data shortfall, a rough approximation which partially offsets this problem had to be developed. A significant observation from the research of Eguchi (1991) on the performance of various pipeline materials is that the shape of the damage-ratio curves is consistent across shaking level. Thus, the pipeline repair rates were corrected based on data on the pipeline repairs following the Loma Prieta earthquake. This "corrected" repair rate was then applied to the future earthquakes being examined, based on the assumptions that the mix of water pipeline materials has not changed significantly since that earthquake and is reasonably consistent throughout the region. The following table shows the pipeline repair rates used for this project.

Use of these repair rates requires knowledge of the ***length of pipeline*** available for rupture. Since a comprehensive map of water transmission and distribution lines is not available, this network was approximated using the local street network, as mapped by the TIGER files of the

U.S. Bureau of the Census. However, pipelines were not assumed to occur under freeways and freeway access ramps, or under dirt roads.

TABLE 19: Approximate Relationships Among Modified Mercalli Intensity, Average Acceleration Spectral Level, Peak Velocity and Pipeline Repair Rates

Modified Mercalli Intensity (as shown on maps)	Average Acceleration Spectral Level (in cm/sec)	Peak Velocity (in cm/sec)	Pipeline Repair Rates (in # repairs/km)
XII - Extreme Damage with Large Amounts of Ground Failure	(more than shaking related)		
XI - Extreme Damage with Moderately Large Amounts of Ground Failure	(more than shaking related)		
X - Extreme Damage	450	286	1.2
	300	191	
IX - Heavy Damage	204	130	0.4
	141	90	
VIII - Moderate Damage	96	61	0.3
	66	42	
VII - Nonstructural Damage	45	30	0.03
	30	19	
VI - Objects Fall	21	13	0.003
	15	10	
V - Pictures Move	9	6	0

Using the estimation from this table, together with the data on kilometers of pipeline estimated for the Loma Prieta earthquake, one obtains an estimate of 607 total repairs for the nine Bay Area counties, which approximates the actual repairs in this area of 580.

Correlating Water Pipeline Rupture Hazard and Road Closures

Although there were approximately 1,200 water pipeline repairs resulting from the Loma Prieta event in both the Monterey Bay and San Francisco Bay regions, only *17* road closures resulted from these leaks. The primary break was on a 60-inch raw water transmission line in the East Bay (El Sobrante). The post-earthquake repair work caused a partial road closure. Many water lines were ruptured in the City of Alameda, with as many as two-to-three of these in one block. While the street itself was not closed, responding vehicles clogged the road segment while repairs were completed.

In the Northridge earthquake, the 1,700 water pipeline repairs resulted in *18* road closures. These represented about one percent of actual water line leaks.

Although a sophisticated analysis of road closures might point out correlations with water pipeline size, material, leak size or other variable and the frequency of road closures, such an analysis is beyond the capabilities of this project. The model to be used relies on simplifying determining the fraction of road closures per pipeline repair for the two earthquakes, that is, (17

+ 18) ÷ (1200 + 1700) or ***0.012***. This fraction can then be applied to a model of total pipeline repairs to estimate the number of road closures by scenario.

Prediction of Road Closures Due to Water Pipeline Rupture by Earthquake Scenario

Using the chart for repairs per kilometer of pipeline, together with the number of kilometers of pipeline exposed to each shaking level, it is possible to estimate the number of repairs for each of the future earthquake scenarios being examined. These predictions are shown in the following table. Then, as a second step, the fraction of those repairs which result in road closures has been estimated.

TABLE 20: Prediction of Number of Road Closures Resulting from Water Pipeline Ruptures for Selected Earthquake Scenarios

EARTHQUAKE	Total Pipeline Ruptures (From Shaking Only)	Total Road Closures
Actual Loma Prieta (10-county area)		17 (some associated with ground failure)
Actual Loma Prieta (9-county area)		17 (some associated with ground failure)
Predicted Loma Prieta (9-county area)		7
San Andreas Peninsula	1,970	24
San Gregorio	588	7
Northern Hayward	2,644[27]	32
Southern Hayward	3,158	38
Entire Hayward	4,980	60
Healdsburg-Rodgers Creek	1,632	20
Maacama	317	4
West Napa	692	8
Concord-Green Valley	1,801	22
Northern Calaveras	1,482	18
Greenville	675	8

Expected Duration of Road Closures Due to Water Pipeline Ruptures

It is difficult to know of precisely how long roads will have to remain closed after a water main rupture. However, based on data from the Northridge and Loma Prieta earthquakes, closure time averaged ***41*** days or roughly 1 1/2 months! The data from the Marina District were complicated by the existence of multiple problems in the same area. Thus, in some of the smaller scenario earthquakes, this estimate is probably high. However, the three Hayward events may produce interrelated damage patterns in large areas of Bay mud and along the fault in the East Bay hills.

[27] This value is reasonably consistent with the analysis performed by the East Bay Municipal Utilities District (1994), which estimated that there will be approximately 990 pipeline repairs ***in their district*** due to ***shaking*** damage as a result of the Hayward earthquake scenario. [EBMUD (1994, pg. 182) estimates an additional 1,309 water pipeline repairs due to liquefaction, 1,562 due to landslides, and 167 due to fault crossings.]

References

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ROAD CLOSURES DUE TO MAJOR GAS PIPELINE LEAKS

Background

Leaks occur in underground gas pipelines in earthquakes, due primarily to shaking-induced ground deformation. The process is very similar to the failure of water lines. As with water lines, a small percentage of these ruptures are in a location or of a size that the adjoining roadway is closed. ***The purpose of the modeling being described in this section is to predict the location of these ruptures and associated road closures.***

The emphasis of this model is on the prediction of significant leaks due to shaking-induced ground deformation. Low levels of shaking-induced ground deformation can produce damage to buried pipelines, and associated leaks, particularly to brittle pipelines, such as those constructed of cast iron.

A total of ***1,094 leaks were found and recorded during the first two weeks following the Loma Prieta earthquake*** (from October 17 to October 31, 1989) (Phillips and Virostek, 1990)[28]. The breakdown of leak location for this earthquake is:

- 207 - East Bay Region (approximately Alameda and Contra Costa Counties)
- 562 - Golden Gate Region (approximately San Francisco and San Mateo Counties)
- 327 - Mission Trail Region (approximately Monterey, San Benito, Santa Cruz, and Santa Clara Counties)

Southern California Gas attributed ***834 leaks to the Northridge earthquake***, including 563 related to corrosion (some of which probably existed prior to the earthquake).

Source:
M. Rymer, U.S. Geological Survey
Water and Natural Gas Pipeline Breaks, Balboa Bl.
Northridge, Calif. Earthquake of Jan. 17, 1994

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[28] These data, from Pacific Gas and Electric Company, are contained in a report which provides several precautions to be taken if using these data:

- "The number of the recorded leaks specifically attributable to the earthquake is unknown.
- Not all leaks found were necessarily reported because of the nature of the emergency.
- Leaks may continue to develop or existing leaks may continue to be discovered due to post-earthquake settling of the soil.
- The earthquake found weak points in the system. Some of the leaks found may have been inevitable; the earthquake just accelerated the process.
- Leak surveys were not performed on the San Francisco Marina District and Watsonville low-pressure systems that were shut-in and replaced."

Only a small fraction of the leaks in these two earthquakes caused a road to close – ***none*** in Loma Prieta and 7 (0.84%) in Northridge. (If roads in the Marina District of San Francisco, as well as Los Gatos and Watsonville, had not already been closed for other reasons following the Loma Prieta earthquake, some of these roads would likely have been closed due to natural gas leaks, however.)

Assessing the Hazard of Gas Pipeline Leaks and Associated Road Closures

One technique for estimating the number of road closures in future Bay Area earthquakes would be to first estimate the number of gas pipeline repairs (based on shaking strength and pipeline type), and then estimate the number of those failures that resulted in road closures. This technique is parallel to that presented in the section on "*Road Closures Due to Water Pipeline Ruptures*."

Given the small number of closures related to the hazard, the decision was made to use a very simple model. Two observations are crucial in this simplification:

- water and gas pipeline leaks tend to occur in areas subject to similar earthquake hazards; and
- the total number of closures associated with natural gas from the two earthquakes (7 closures) is 20% of the total roads closed due to water pipeline ruptures (35 closures).

Thus, the water pipeline closure number was multiplied by 0.20 to yield the gas pipeline closures. The following table shows the results of this simple model.

TABLE 21: Prediction of Number of Road Closures Resulting from Gas Pipeline Ruptures for Selected Earthquake Scenarios

EARTHQUAKE	Estimated Road Closures due to Gas Pipeline Ruptures
Actual Loma Prieta	0
Predicted Loma Prieta (9-county area)	1
San Andreas Peninsula	5
San Gregorio	1
Northern Hayward	6
Southern Hayward	7
Entire Hayward	12
Healdsburg-Rodgers Creek	4
Maacama	1
West Napa	2
Concord-Green Valley	4
Northern Calaveras	4
Greenville	2

A Note on Pipeline Performance Related to Pipeline Type

Several factors affecting pipeline performance relate to pipeline type, including:
- material;
- type of weld or joint;
- size; and
- condition.

There is a correlation of pipeline damage to pipe material: cast iron, steel, or polyethylene (PE) plastic. Cast iron pipes (particularly joints) are susceptible to leakage and subsequent earthquake failures. The only locations where significant amounts of cast iron pipe remain in the Bay Area in areas subject to liquefaction are in Santa Clara and northern San Jose (oral communication, W. Savage, April 1997). Extensive systems of cast iron lines experienced numerous leakages in the Marina, Los Gatos and Watsonville and were replaced following the Loma Prieta earthquake with plastic (PE) and welded steel pipe. Newer gas pipelines in common use have performed extremely well under severe shaking and substantial ground deformation.

TABLE 22: Pacific Gas and Electric Company Gas Distribution System Pipe Materials in 1988 (Prior to the Loma Prieta Earthquake)
[from Phillips and Virostek, 1990]

Material	Steel	Cast Iron	Plastic (PE)
Main Length (in miles)	22,428	783	9,436

Welds and joints between segments of gas pipelines are a more common source of leaks than the pipe body itself. Welds are of three types: oxy-acetylene, unshielded arc, and shielded arc.
- Prior to the 1930s, oxy-acetylene welds were used for girth welding on transmission lines. These types of welds have the worst earthquake performance. O'Rourke and Palmer (1996) note that approximately 91% of non-corrosion leaks not in areas of ground failure in eleven southern California earthquakes were due to ruptures in pre-1945 oxy-acetylene girth welds.
- Unshielded arc welding, in vogue for a short period after 1930, resulted in uneven heating and defects. The quality of these welds was thus reduced enough to pose a vulnerability problem under some seismic conditions.
- Use of shielded arc welding began in the 1930s. By the end of the second World War (around 1945) shielded electric arc welding became the norm. Shielded arc welds have performed extremely well in southern California earthquakes. However, experience in other regions has shown that these types of welds are not invincible under permanent ground deformation, such as severe landslides.

As noted above, there were 834 leaks detected following the 1994 Northridge event, many of which were attributed to corrosion or materials problems. Only 271 were not related to corrosion and other material problems. Of these, 35 repairs were made to larger transmission lines, 71% (25/35) were in pre-1932 pipelines at oxy-acetylene welds (O'Rourke and Palmer, 1996). Of the breaks in distribution mains, 89% (209/236) were in metal mains and only 11% (27/236) in plastic mains (EERI, 1995). At least two of these distribution line breaks were due to permanent ground deformation – landslide and lateral spreading.

The principal reason that this pipeline-type information is not included in this analysis is the small percentage of these repairs that result in road closures.

Although there were approximately ***834 gas pipeline repairs*** in the Northridge earthquake, only ***seven road closures*** resulted from these leaks. These represent about 5% of the road closures in that earthquake, and 9% of the closures due to indirect hazards in that earthquake. The most well-known was a 22-inch steel pipeline with unshielded arc welds under Balboa Boulevard (Line 120) which ruptured in two places due to extensional ground failure – one in tension and a second in compression about 900 feet from the first. Sparks from a pickup truck ignited the gas, which burned five houses and closed the street. The same ground failure caused to water line ruptures, which contributed to the problem (USGS, 1996; EERI, 1995; O'Rourke and Palmer, 1996). Balboa was closed or partially closed for a total of 62 days. (Damage to the road due to the water line rupture was more extensive than due to the gas pipeline.) In another series of failures, a 12-inch pipe conveying gas between Newhall and Fillmore (Line 1001) experienced 24 breaks at oxy-acetylene welds and one buckled section. Gas escaping from one of these ruptures under State Route 126 ignited (due to a downed power line) and blew a hole in the road (EERI, 1995; O'Rourke and Palmer, 1996). Because the road was repaired in a few hours, it does not appear in the attached database (Appendix B).

As stated earlier, there were ***1,094 gas line repairs*** made by Pacific Gas and Electric following the Loma Prieta earthquake, ***as well as replacements of the entire network in portions of the Marina District in San Francisco and in Watsonville.*** No roads were known to be closed due to gas leaks alone. As stated earlier, if roads in the Marina District of San Francisco, as well as Los Gatos and Watsonville, had not already been closed for other reasons following the Loma Prieta earthquake, some of these roads would likely have been closed due to natural gas leaks, however. In the Marina, for example, road closures were due primarily to liquefaction, structure problems and associated fires, rather than directly due to ruptured mains or transmission lines.

Expected Duration of Road Closures Due to Gas Pipeline Ruptures

As with water pipeline-related road closures, it is difficult to know precisely now long road will remain closed after a gas line rupture. Based on data from the Northridge and Loma Prieta earthquakes, closure time averaged ***12 days***. This time period is far less than the 41-day average for water pipeline ruptures. If the Balboa Blvd. closure in the Northridge earthquake (which was also caused by a water pipeline rupture) is removed from this calculation, the average closure time is reduced to approximately ***4 days***. This closure time is due to repair of the leak itself (which typically takes less than a day), as well as repair to the road surface.

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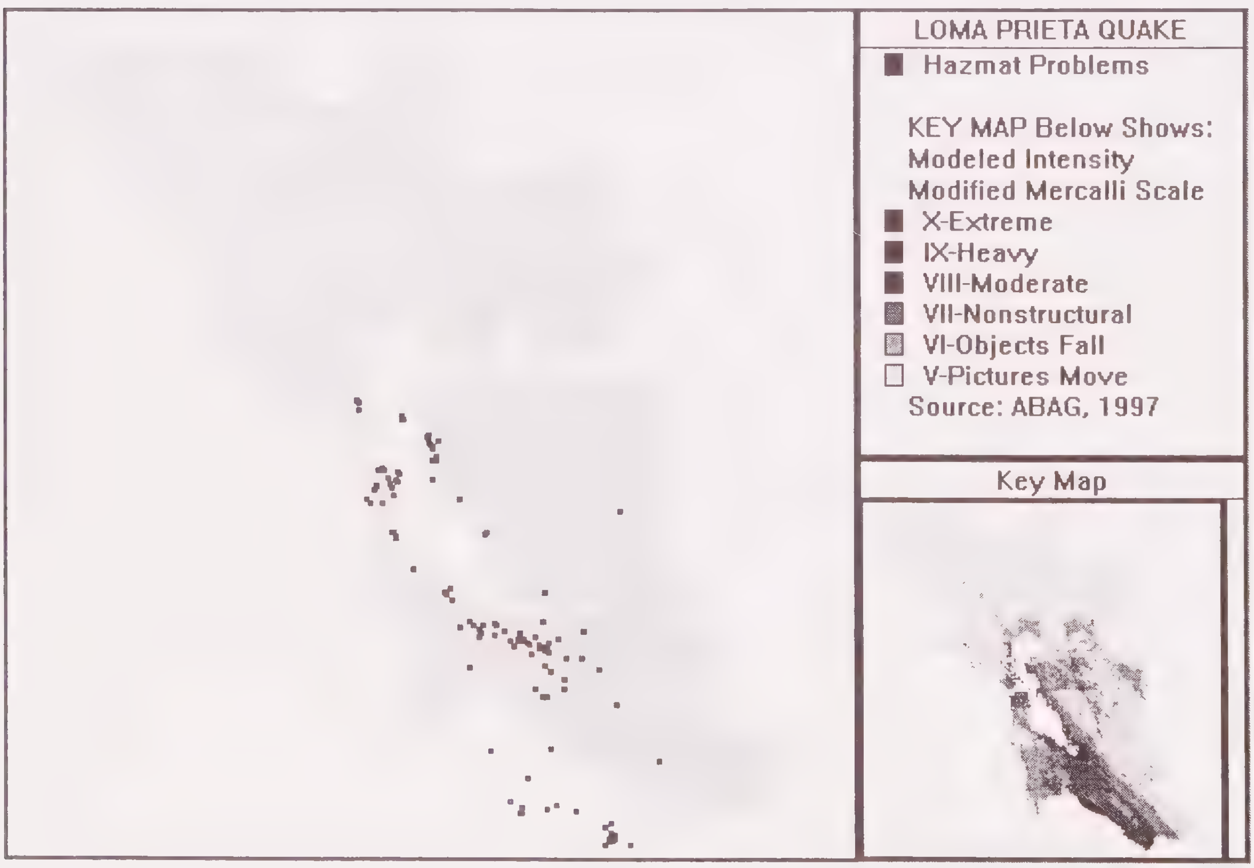
Oral communications also occurred with Woody Savage (Pacific Gas and Electric Company) regarding the location of cast iron pipe in areas of soft soil (April and May, 1997).

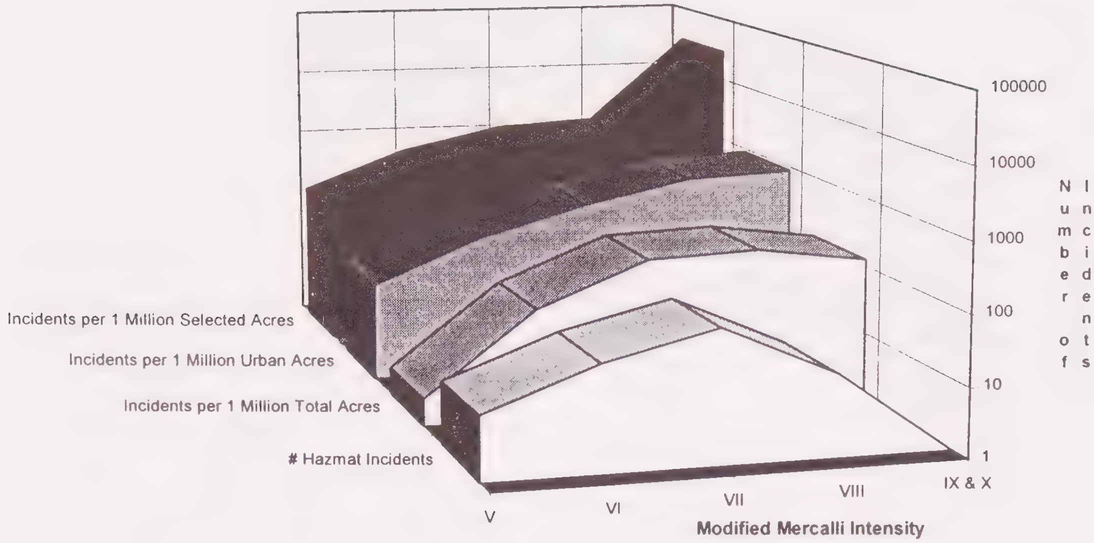
Road Closures Due to Hazardous Materials Releases

One of the most difficult indirect hazards to predict, even in terms of its overall hazard in an earthquake, is hazardous materials releases. The principal reasons for this difficulty are the incomplete data on past hazardous materials releases, the causes for those releases, and the resulting road closures, if any. In addition, the overall extreme rarity of these closures makes any form of statistical analysis difficult.

The most complete databases of both road closures and hazardous materials releases are available for the two most recent disastrous California earthquakes, the 1989 Loma Prieta earthquake (Perkins and others, 1990) and the 1994 Northridge earthquake (Selvaduray, 1996).

Overall, several dozen hazardous materials problems occurred in Loma Prieta. However, two types of spills were removed from the database prior to using it in this project – residential releases and asbestos releases – because it is unlikely that any spills related to these two types of problems would be sufficient to close a road. Thus, for purposes of this analysis, one is left with 134 spills. These spills did not occur randomly throughout the Bay Area. The challenge is to determine some simple correlations between number of spills and location without stretching the statistical limits of the data. The following map depicts the location of those problems.





Hazmat Incidents in the Loma Prieta Earthquake by Ground Shaking Intensity Level

As shown in the figure above, ***the number of hazardous materials incidents has no direct correlation with ground shaking intensity level***, resulting in the number of hazmat incidents actually decreasing at higher intensities. However, if these incidents are normalized using total acres exposed to each intensity level, a correlation begins to show. This correlation becomes stronger as one becomes more specific about the type of land use area being exposed, first to total ***urban*** acres, and then to ***selected*** urban acres (urban acres not including residential or urban open space).

The correlation between numbers and severity of hazmat incidents in earthquakes to acres of selected urban land can be used with predictions of these land areas exposed to various intensity levels in future earthquakes to predict the number of hazmat incidents in those earthquakes, as shown in Table 23 and 24, below.

TABLE 23: Number of Acres of Selected Urban Land per Hazmat Incident for Loma Prieta
[where selected urban = urban acres not including residential or urban open space]

INTENSITY LEVEL (as modified Mercalli intensity)	V	VI	VII	VIII	IX - X
Number of Acres / Hazmat Incident	7,763	2,005	910	724	35
Number of Hazmat Incidents / Acre	.00013	.00050	.00110	.00138	.02857

TABLE 24: Acres of Selected Urban Land Exposed to Each Intensity Level and Resulting Prediction of Number of Hazmat Incidents in Selected Earthquake Scenarios
[where selected urban = urban acres not including residential or urban open space]

EARTHQUAKE	Selected Acres Exposed to Intensity V	Selected Acres Exposed to Intensity VI	Selected Acres Exposed to Intensity VII	Selected Acres Exposed to Intensity VIII	Selected Acres Exposed to Intensity IX-X	Predicted Number of Hazmat Incidents
Actual Loma Prieta[29]	62,104	64,149	70,965	10,853	35	134
San Andreas Peninsula	52,920	55,645	59,140	45,891	2,268	229
San Gregorio	56,235	88,561	58,780	11,459	832	156
Northern Hayward	14,087	69,356	77,989	26,205	28,230	974
Southern Hayward	21,054	59,327	54,824	50,019	30,642	1047
Entire Hayward	5,145	40,929	66,733	50,753	52,307	1676
Healdsburg-Rodgers Creek	21,058	115,433	43,669	28,445	7,262	357
Maacama	112,831	65,781	35,737	1,512	5	89
West Napa	56,421	103,036	44,888	6,860	4,663	252
Concord-Green Valley	13,036	79,727	83,284	27,867	11,952	517
Northern Calaveras	23,416	76,087	84,417	25,535	6,412	354
Greenville	36,009	98,172	69,507	10,516	1,664	193

The next step is to predict the number of these releases that are likely to result in road closures. No such closures occurred in the Loma Prieta earthquake, even due to the release of 5,000 pounds of anhydrous ammonia from a refrigeration system in Watsonville, or due to the release of 1.7 million pounds of sodium silicate (caustic) from a chemical facility in Berkeley.

Even though the data from the Northridge earthquake could not be used in the earlier analysis because it cannot be tied to intensity/land use data at the present time, the data can be used to help predict the number of hazardous materials problems resulting in road closures. In that earthquake, 190 hazardous materials problems occurred (excluding residential and asbestos). In addition, only 3 areas of roads were closed. If one adds the Loma Prieta and Northridge data, a total of 324 (or 190 + 134) problems occurred, with three road closures. Thus, approximately 1% (or 3/324) of the known hazardous materials problems result in road closures. As a second check on this estimate, ABAG collected information on the total number of Bay Area road closures not due to earthquakes, as well as the total number of hazardous materials problems, during 1995 and early 1996. The annual ratio of 7 road closures in the 12 months of 1995 to 1996 versus 1689 in a 20-month period is also roughly 1% (7/1013). The results of this analysis are shown in Table 25.

[29] Note that the total number of selected acres is different for this earthquake than the following eleven future earthquake scenarios. ABAG updates its file of existing land use every five years (Perkins and Chuaqui, 1996). The 1990 land use file was used in the analysis of the 1989 Loma Prieta earthquake, while the 1995 file was used in the analysis of the subsequent earthquake scenarios.

TABLE 25: Prediction of Number of Hazmat Incidents in Selected Earthquake Scenarios Resulting in Road Closures

EARTHQUAKE	Predicted Number of Hazmat-Related Road Closure Incidents[30]
Actual Loma Prieta	0
Predicted Loma Prieta (9-county area)	1
San Andreas Peninsula	2
San Gregorio	2
Northern Hayward	10
Southern Hayward	10
Entire Hayward	16
Healdsburg-Rodgers Creek	3
Maacama	1
West Napa	2
Concord-Green Valley	5
Northern Calaveras	3
Greenville	2

It is extremely important to understand that these values are estimates, and can be easily be incorrect by a factor of two or more.

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[30] Note that these values may be slightly less than 1% of the total hazmat incidents due to rounding errors in the tract-by-tract calculations.

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Road Closures Due to Dam Failure

Dam failures can result in the worst flood events. A dam failure is usually the result of neglect, poor design, or structural damage caused by a major event such as an earthquake. When a dam fails, a gigantic quantity of water is suddenly let loose downstream, destroying anything in its path. For example, in 1889, more than 2,200 lives were lost as a result of the Johnstown, Pennsylvania flood caused by an upstream dam failure. Billions of dollars of property damage can also occur as a result of a dam failure.

More recently, in 1971, during the San Fernando earthquake, shaking caused a major slide of the top thirty feet of the Lower San Fernando Dam. The dam was very close to completely failing. Eighty thousand people living downstream of the dam were immediately ordered to evacuate. At the time, there were no dam failure inundation maps available showing the areas which would be affected by a dam failure, and there were no planned evacuation procedures to follow.

As a result of the near failure of the Lower San Fernando Valley Dam, the Dam Safety Act was passed into law. This new law required dam owners to create maps showing areas that would be flooded if the dam failed. The California Office of Emergency Services (OES) approves the maps and distributes them to local governments, who in turn are required to adopt emergency procedures for the evacuation and control of areas in the event of a dam failure.

Besides the passage of the Dam Safety Act, other improvements concerning dams have been made throughout California as a result of the near-failure of the Lower San Fernando Valley Dam. Hydraulic fill dams, the type of dam that the Lower San Fernando Valley Dam was, were deemed to be unsafe and have been replaced with other types of dams (usually rolled earth dams in the Bay Area). Various other standards for dam structures have been improved and applied.

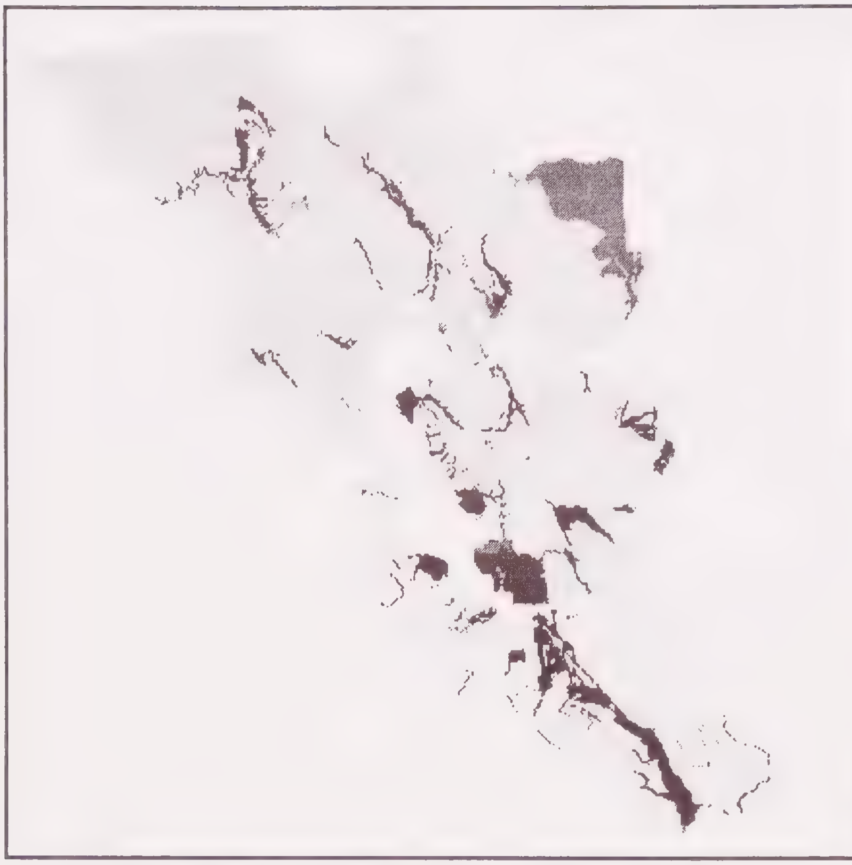
Because of these changes, it is extremely unlikely that any dams will fail in future earthquakes. Rather than coming up with a model trying to estimate this minuscule risk, it is more appropriate to merely identify areas which would be affected by a dam failure.

Before making these plans using the inundation maps, one should be aware of the following information.

- The maps were developed by dam owners to fulfill state law requirements. The maps are intended for emergency planning purposes.

- The maps were developed using engineering hydrology principals and represent the best estimate of where the water would flow if the dam completely failed with a full reservoir. The inundation pathway is based on completely emptying the reservoir and does not include run-off from storms.

- Many of the maps were developed in the 1970's. Should the maps have been developed more recently, different assumptions and map-making methods would likely have been used.



HAZARD MAP

DAM FAILURE
INUNDATION AREAS

Source: ABAG, 1995
This hazard map is generalized from maps dam owners are required to prepare and file with the State Office of Emergency Services. The map is intended for planning only. Current version of this map is available on Internet at http://www.abag.ca.gov

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Road Closures Due to Assorted Hazards – Freeway Hazard, Traffic Control and Other Causes

Background

During both the Loma Prieta and Northridge Earthquakes, there were a significant number of roads which closed due to:

- hazards posed by damaged freeway structures within urban areas;
- emergency traffic flow requirements within damaged urban areas; and
- other circumstances.

Damaged freeway structures can close not only themselves, but roads which are adjacent or in close proximity to them. These closures are defined as ***freeway hazards***. During the Loma Prieta earthquake, for example, streets which were adjacent to or under the Embarcadero freeway in San Francisco and the Cypress structure in Oakland were closed because of the hazards posed by these damaged structures. Similarly, during the aftermath of the Northridge earthquake, streets which were adjacent or went under damaged freeway structures on State Route 118 and Interstate 405 were closed because the structure had collapsed and blocked the roads or because these structures were sufficiently damaged to be a safety concern.

In the aftermath of both the Loma Prieta and Northridge earthquakes, portions of streets were closed to facilitate ***traffic flow***. For example, sections of Market Street in downtown San Francisco were closed from intersection to intersection between First and New Montgomery streets. These closures facilitated north- and south-bound traffic flow across Market.

In addition to these closures, there were streets which closed because of unusual circumstances (such as a train derailment or snapped electrical lines) or for unknown reasons. These closures are grouped as ***other hazards***.

All together, closures due to freeway hazard, traffic control and other causes represented 25 percent of all of the road closures which occurred during the Loma Prieta and Northridge earthquakes.

Methodology for Assessing Closures due to Freeway Hazard, Traffic Control and Other Causes

Because the causes for these closures tend to originate with the hazards described in earlier sections, these assorted causes are being modeled as aggregations over the numbers generated by the rest of the direct and indirect hazards.

Because ***freeway hazard*** is closely related to shaking, it is being modeled as a fraction of the freeways which closed due to shaking. This fraction was derived by dividing the total number of closures due to freeway hazards in both the Northridge and Loma Prieta earthquakes (28) by the total closures due to shaking damaged structures in those two earthquakes (61), or ***0.459***. Thus, the number of roads which are closed due to freeway hazards is obtained by using the predicted

number of freeway closures due to shaking damage for each earthquake scenario and multiplying it times this fraction.

Closures due to ***traffic control and other*** have been combined into one model and have followed a similar methodology as freeway hazard. Because they are not necessarily associated with any particular hazard the way freeway hazard is associated with shaking, these categories are modeled as a fractional increase to the sum of all of the other causes of predicted closures. The fractional increase was derived by adding the total traffic control and other closures from Loma Prieta and Northridge (44), and dividing by the subtotal of closures not including these causes (238), or ***0.185.*** Thus, the number of roads which are closed due to a traffic control and other is obtained by using the subtotal of closures due to all other causes for each earthquake scenario and multiplying it times this fraction.

Source:
J. Perkins, Assoc. of Bay Area Governments
Northridge, California Earthquake of Jan. 17, 1994

Prediction of Road Closures Due to Freeway Hazard, Traffic Control and Other Causes

The results of the techniques described above provide the following results for the scenario earthquakes.

TABLE 26: Prediction of Number of Road Closures Due to Freeway Hazards and Other Assorted Causes

EARTHQUAKE	Predicted Road Closures due to Freeway Hazards	Predicted Road Closures due to Traffic Control and Other Causes
Actual (9-county) Loma Prieta	15	25
Predicted (9-county) Loma Prieta	11	22
San Andreas Peninsula	27	67
San Gregorio	11	34
Northern Hayward	50	140
Southern Hayward	58	126
Entire Hayward	81	232
Healdsburg-Rodgers Creek	20	55
Maacama	4	11
West Napa	8	22
Concord-Green Valley	21	53
Northern Calaveras	23	45
Greenville	10	19

Expected Duration Road Closures Due to Freeway Hazard, Traffic Control and Other Causes

It is difficult to know precisely how long roads will have to remain closed after one of these incidents. Data from Loma Prieta and Northridge indicates that there are differences in the length of time between these three categories. Roads closed due to freeway hazard have tended to remain closed for almost three months (79 days). Traffic control closures have remained closed for approximately one month after the event (35 days). Those closed due to unusual or unknown causes have only remained closed for less than one week (six days).

WHO ARE THE KEY TRANSPORTATION USERS IN EMERGENCIES ?

Overview

The process of identifying transportation system ***users*** is the first step in identifying the ***demand*** side of a supply-demand analysis for post-earthquake transportation facilities. Such users include the providers of transportation (other than the street and highway system), as well as agencies integral to emergency response.

Transportation users include:

Transportation-Related	Response-Related
	Emergency Health Care
Air Transportation	Fire, Police and Emergency Operations
Marine Transportation	Public Mass Care (Shelter and Feeding)
Rail Transportation	Water Supply
Transit	Wastewater Treatment
	Electric Power and Natural Gas
	Telecommunications

In general, these transportation users will be traveling to points, such as offices, maintenance facilities, and stations, as well as to lines, whether they are transit routes, water lines, or natural gas lines. Because the lines or routes tend to be pervasive throughout the region, they are of little use in an analysis focusing on determining concentrations of facilities. Thus, the following discussion (and the analysis that follows), focuses on the type and location of these point facilities.

It is also important to know the types of problems these facilities have experienced in past earthquakes; past experiences can be used to help predict how operators of these facilities will be using the transportation system to respond to these future problems.

Each of these eleven users are described on the following pages.

Air Transportation Facilities

Introduction

Air transportation is crucial to the Bay Area economy, both in terms of movement of passengers and of air cargo. Air facilities are generally divided into four categories – commercial airports, general aviation airports, private airfields, and special-use airports. Military airfields are also part of the region's air transportation mix.

In the Bay Area, three large airports serve both domestic and international markets. San Francisco, Oakland, and San Jose International Airports are served by commercial airlines which offer flights to airports around the globe. Although commercial airports are usually viewed as passenger transit points, a substantial volume of cargo is also transported on commercial flights, private carriers, and by mail and package companies.

Airport facilities can provide a great advantage after a natural disaster. In the event of an earthquake that results in major damage to ground transportation systems, access to the airways can offer a means of obtaining needed supplies and services.

However, local roads and rail lines must remain operational for the goods to be distributed to the affected communities. ***Movement of goods through airports relies as much on the transportation system connected to the airports as on the airport operations themselves.*** In the hours and days following an earthquake, transporters of air cargo rely on rail lines and freeways to begin the distribution of needed goods and supplies received at airports. The commercial air freight sector is thus highly dependent on other transportation links.

Commercial Airports

San Francisco International Airport is the largest airport in the region, both in number of yearly passengers and in the economic value of cargo. Located on a site of about 5200 acres, the airport has four runways ranging in length from 7000 to 11,800 feet. It is host to over 430,000 flight each year, carrying 31 million passengers. In addition, more than 615,000 metric tons of air cargo, worth $25 billion, are shipped through the airport annually.

Oakland International Airport consist of two airfields – the South Field for commercial flights, and the North Field for general aviation. The South runway is 10,000 feet long. While the three North runways are shorter than 7000 feet, two of the three are longer than 5000 feet. Nine million passengers are served by this facility. Air cargo of 565,000 metric tons, worth $9 billion, was transported through the airport in 1995.

San Jose International Airport covers 1,050 acres, with 3 runways. Twelve airlines use San Jose, as do five air freight/air cargo companies. Commercial aircraft are the primary users for the 10,200 foot, primary instrument runway. Business aircraft and general aviation aircraft use the

two other runways, each under 5000 feet. Approximately 8.4 million passengers use San Jose International yearly, and 94,000 tons of cargo pass through this airport.

Other Airfields

The Bay Area's air transportation resources are plentiful and diverse. In addition to the commercial airports described above, 22 general aviation airports operate in the ten counties (including Santa Cruz). These facilities are not served by scheduled air carriers nor air cargo services, but they accommodate private planes and corporate aircraft. Some may offer limited air taxi service. Although runways at most of these airports generally range from 2000 to 3500 feet in length, four of the 22 have runways of at least 5000 feet.

The Bay Area is home to a total of 14 small private airfields. These fields have short runways, which are often unpaved, and little or no support facilities. Small, propeller-driven aircraft are about the only type of plane that can use these airfields.

Some of these airports allow the use of aircraft other than airplanes. All three commercial airports also have heliports, for example, and 13 of the general aviation facilities also permit use of helicopters. Also, two fields are allowed to service glider traffic--one exclusively. Finally, seaplanes operate from one facility in Marin County.

Four military airports share the airspace in the Bay Area and have been for decades; however, the future status of three of them is uncertain at this time. These are Travis Air Force Base, Alameda Naval Air Station, Moffett Field, and Hamilton Field. Travis Air Force Base will remain open after the expected base closures of the other facilities are completed. It is important to note that all four of them have runways of at least 8000 feet.

The issue of runway length is an important one, as 5000 feet is considered the minimum length which will allow takeoff and landing of small passenger or cargo jets, such as a Boeing 727 or 737, or MD-80. Larger jet aircraft, such as Boeing 757s, require about 7500 runway feet.

Location of Airport Facilities

This map depicts 55 mapped airport facilities in the Bay Area, including:

- 3 commercial airport passenger terminals
- 2 commercial airport air cargo facilities
- 2 commercial airport airline maintenance facilities
- 3 commercial airport runway areas
- 2 commercial airport utility areas
- 3 commercial airport areas used for other
- 22 public (general aviation) airfields
- 13 private airfields
- 2 military airports
- 3 closed military airports (with airfields intact)

Thus, commercial airports have not been given preference over general aviation and private airfields directly. However, the three commercial airports contribute 15 of the 55 mapped facilities.

Bay Area Air Transportation Facilities

Experience in the Loma Prieta Earthquake

Although operations at San Francisco officially halted after the Loma Prieta earthquake for one night, this was not due to any significant damage to the facilities. The control tower sustained window and non-structural damage, and some unanchored equipment was broken, but this did not prevent it from operating. ***The primary reason for the shutting down of flights during that night was that not enough controllers were available to operate the tower safely.*** The runways (built on fill), navigational equipment, runway lights, fuel tanks, and piping were unaffected, except for liquefaction shifting some small support structures. Lost power was restored within 3 hours, well before the time the airport was reopened. Non-structural damage occurred in the terminals, but did not cause the airport to be shut down. Damage to an air cargo building was significant, and problems transpired with a power transformer, but these were remedied over time without air operations being affected. ***There were no problems with access road failures or freeway closures within the immediate vicinity of this airport that contributed to closure. However the ability of the controllers to travel to work safely and quickly was an issue.***

The Oakland Airport was more affected by the Loma Prieta earthquake than the San Francisco Airport. Its main runway, on hydraulic fill over Bay mud, had severe liquefaction damage; 3000 feet of this surface sustained cracks, some of them a foot wide with nearby ground cracks up to ten feet deep. Several vertical offsets appeared on the runway, some approximately one foot high. Large sand boils appeared, a few as wide as 40 feet. As a result, the airport was immediately shut down to evaluate runway damage. The shorter general aviation runway was used to accommodate diverted air traffic for a couple of hours before the main runway was reopened with a usable length of only 7000 feet. Over the next few months, the runway was repaired and most of its original length restored, using an emergency repair order for resurfacing and crews already present during the earthquake. An adjacent taxiway was also damaged by liquefaction. This segment, plus the final 1500 feet of the main runway, were repaired several months later after a competitive bidding process. Communications were difficult at Oakland, as both telephone service and the usable radio frequency became quickly overloaded. The problems with communications affected both cleanup crews and the public inside terminals. Damage to the control tower was limited to the loss of three windows, a walkway between terminals was damaged, and a water main rupture caused a service road to collapse. These problems did not affect airport operations.

The control tower at San Jose lost a window and had non-structural problems; other cosmetic damage occurred at the terminal. Commercial power was lost for over 5 hours, but backup generators worked well. None of the problems affected operations, which were shut down only briefly to assess damage. The airport was considered as an alternative airfield if flights needed to be diverted from San Francisco or Oakland. The main reason this did not occur was the lack of refueling capabilities at San Jose (rendering takeoff of most of those planes impossible) rather than problems due to the earthquake. No road failures at or near the airport were reported.

Smaller airfields generally have minimal facilities. No damage was reported at these locations.

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- Mark O'Brien, Manager, Environmental Health and Safety Compliance, and Jane Keegan, Risk Manager, Port of Oakland, October 12, 1995.
- Rosemary O'Kane, San Jose International Airport, May, 1996.
- Mark Roddin, Metropolitan Transportation Commission, summer 1995.

Marine Transportation Facilities

Introduction

Shipping trade is an integral part of the supply of goods to consumers in the Bay Area as well as the export of goods manufactured and traded in many portions of the western U.S. Within the nine-county region, five commercial ports manage both domestic and international cargo.

These ports are generally points through which goods are shipped and received. Products and materials may have originated in cities adjacent to port facilities, in other parts of the Bay Area, in further reaches of northern California, or as far away as Rocky Mountain states for shipment to Pacific ports, Asia, and some U.S. regions. Similarly, consumer items and raw materials received at these ports may be on their way to any of those domestic destinations. Seven military facilities have been located at various points around the Bay as well; the future of these marine sites is not certain enough to be described here.

Because shipping is of significant importance to the regional, state, and national economies, it is essential that maritime commerce facilities remain operational in the event of a natural disaster such as an earthquake.

However, movement of goods through ports relies as much on the transportation system connected to the ports as on the port operations themselves. Goods ready for export cannot reach wharves and docks without adequate operation of rail lines and freeways which are linked to commercial ports. Even more importantly in the hours and days following an earthquake, rail lines and freeways are needed to begin the distribution of needed goods and supplies received at ports. Thus the commercial shipping sector is highly dependent on other transportation links.

Commercial Ports

The Port of Oakland consists of 29 berths in 20 terminals over 475 acres. Sixteen of these terminals have rail connections. Two of the 20 have been military operations (the Army Terminal and the Naval supply Center), but the Port will be taking over the Naval facility in 1997/1998. Fourteen terminals are operated by private companies. This port handles 95% of the goods which pass through the Golden Gate, including containers, breakbulk (non-containerized goods), general cargo, and heavy operations. No natural gas or petroleum is accepted. Other types of business include passenger service (ferries and a small boat harbor), ship towing (tug boats), ship repair, fishing, and commercial (offices and retail, as well as tourist attractions). Shipping operations are the 5th largest in the U.S. by volume, grossing $70 million in revenue in 1995. It is the second largest container port on the Pacific Coast (Marine Exchange, 1996, and oral communication with Mark O'Brien, October 1995).

The Port of San Francisco operations cover 1000 acres and over 7 miles of waterfront, including 14 commercial terminals. Eight are owned by the city, and six are operated privately. Rail

connections are present for eight of the terminals. Import shipping business at San Francisco consists primarily of breakbulk, that is, dry and liquid bulk (paper, coffee, and rice, primarily), as well as automobiles. Some containerized shipping also occurs. About 3 million metric tons of cargo are shipped annually. Exports are dominated by paper, cotton, and animal feeds. Other types of business include passenger service (1 terminal for cruise ships, 5 companies offering bay charters, a small boat harbor, and ferries serving 8 destinations), ship towing (tug boats), ship repair, fishing, and property management (offices, retail, and tourist attractions) (Marine Exchange, 1996, and oral communication with Ben Kutnick, November 1995).

The Port of Richmond is not a full operating port per se; essentially it is run as a land rental operation. Tenants manage most of their own equipment. Six terminal areas are owned by the Port, ten are privately-owned terminals, and one facility is operated by the U.S. government. Municipal terminals are for layberthing and warehousing, bulk liquids, steel and lumber, and containers. Other terminal operations include barges and oil spill cleanup, gypsum, general cargo, and autos. Most of the privately-owned terminals are operations of oil companies. The government installation is the U.S. Naval Fuel Depot at Pt. Molate. Of the public terminals, five of the six are serviced by a rail line. Imports are dominated by autos from Japan, steel from Australia, New Zealand, and Europe, and containers from the South Pacific (including Australia and New Zealand). Operations at the private terminals are dominated by petroleum. Exports are often project cargo; specialized shipments (including such products as geothermal plants, used refinery equipment, and pipe) have been transported in the past year. Recently steel has been going to Chile, and lumber to New Zealand. In 1995, 19 million metric tons passed through the Port (Marine Exchange, 1996, and oral communication with Joe Faber, November 1995).

The Port of Redwood City covers only 95 acres, with five wharves. It handles dry bulk cargo only, and no containers. Most of this cargo is recycled materials, with some salt and agricultural products. It is run mainly as a land rental operation. Southern Pacific rail lines service the Port. The three major tenants manage their equipment. They include scrap metal exports, a gypsum company stockpiling sand, gravel, concrete, asphalt, and gypsum, and U.S. Geological Survey ocean surveying boats. Most of these materials are used in the Bay Area; very little of the shipments are bound for international waters. In fiscal year 1995, the annual volume was just over 765,000 tons annually (443,000 tons exported and 324,000 tons imported), and the revenue was just over $19.5 million per year ($4.3 million from imports and $15.2 million from exports) (Marine Exchange, 1996, and oral communication with Rodney Gadna, October 1995).

Facilities at the Port of Benicia are privately-owned and operated. They consist of three berths, fundamentally for automobiles and petroleum products (Exxon), and some bulk products. Imports and exports total about $4 billion per year (primarily from 200,000 autos). The Port's petroleum product shipments amount to about $50 million annually) (Marine Exchange, 1996, and oral communication with Joe Gaidsick, November 1995).

Ferries

Six ferry operations carry passengers from docks in four counties: Alameda, Marin, San Francisco, and Solano. In Alameda County, ferry docks are located in the City of Alameda (at

the Naval Base and Harbor Bay) and in Oakland (at Jack London Square). In Marin County, these docks are located on Angel Island, as well as in Sausalito and Tiburon. Vallejo has the only ferry dock in Solano County. San Francisco has ferry service from the Ferry Building, Pier 41 1/2, and Pier 48. In addition, several tour operators carry on business from San Francisco piers. Only two public agencies provide water transport services: Golden Gate Transit, and Vallejo Transit. Golden Gate's fleet totals 5 boats, and has on-site maintenance and fuel capabilities at its Larkspur and San Francisco Terminals. Vallejo, operating one ferry, maintains it at its ferry mooring along Mare Island Strait. An additional temporary facility is operated in Berkeley. Some marinas, as well as closed military facilities, have the potential to serve as temporary landings for these or additional ferries.

Other Facilities

The Alameda Encinal Terminal is the largest privately-owned open steamship terminal in the U.S. Consisting of four berths, the terminal has rail connections. Services include general cargo and bulk liquids handling, as well as freight storage.

Local commercial transport using San Francisco Bay includes tugs for assisting in shipping. Sixteen tugboat companies operate 62 vessels in the greater San Francisco Bay Area.

Approximately 100 marinas and harbors are home for innumerable sailboats, yachts, and other pleasure craft in the Bay and Delta. The largest number of small boat berthings in the Bay Area are in the counties of Contra Costa, Alameda, and Marin.

Location of Marine Transportation Facilities

This map depicts 49 mapped marine facilities in the Bay Area, including:

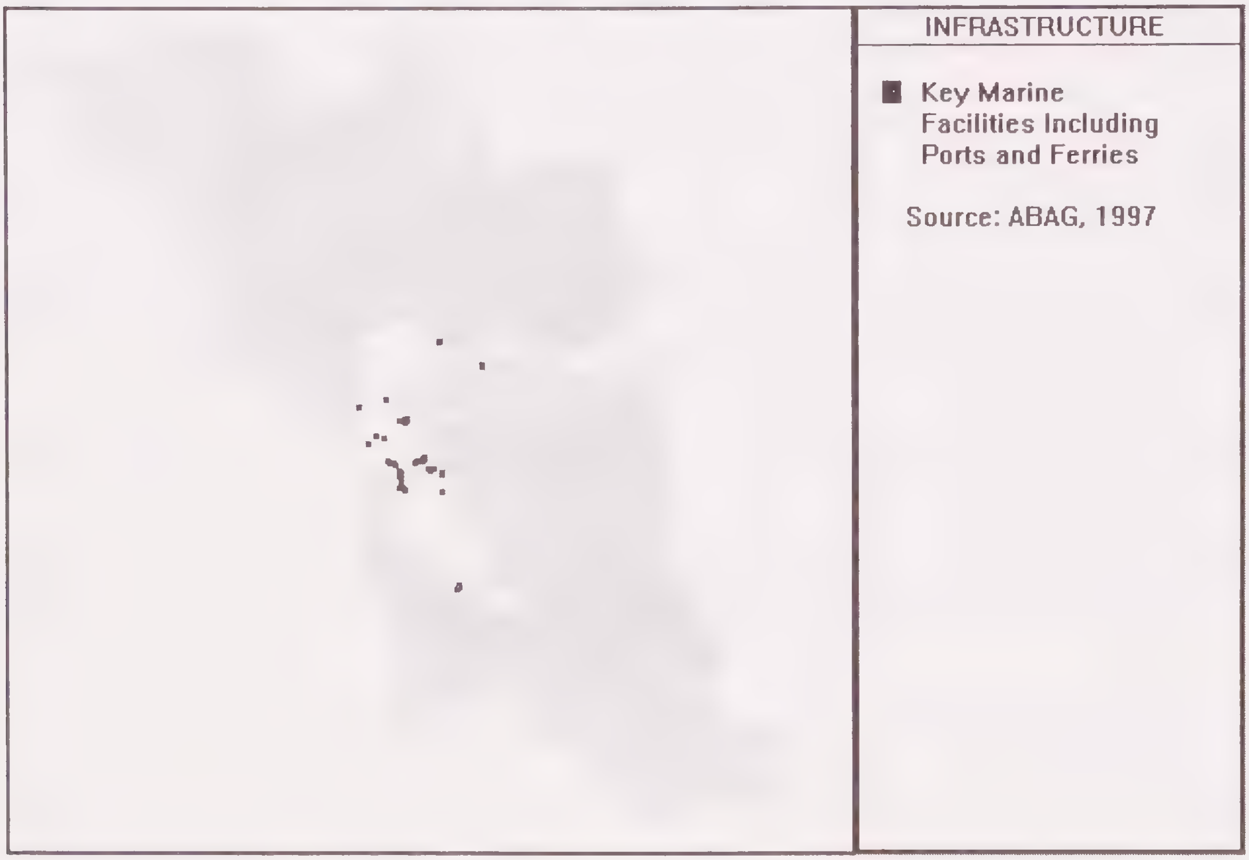
- 1 port passenger terminal
- 11 port container terminals
- 6 port oil and liquid bulk terminals
- 18 port ship repair and other terminals
- 3 port storage facilities or warehouses
- 10 ferry terminals

Experience in the Loma Prieta Earthquake

The Loma Prieta earthquake of October 1989 caused damage to the larger ports in the Bay Area. Problems occurred primarily in fill areas, where broken water and fire lines contributed to problems. Soils affected by liquefaction caused overlying pavement to buckle from both settling and uplifting. Settlement was much more severe under facilities supported by fill than under facilities supported by piles, and soil continued to shift for several days after the earthquake.

In addition to the problems described above, the Port of San Francisco experienced damage to several structures (warehouses at Piers 45 and 48, and an office building on Pier 70) as a result of the Loma Prieta earthquake. Differential settlement affected a few access roads at the Port, and temporary repairs were made to these roads by constructing asphalt ramps over cracks. A total of $8-10 million was estimated for repair of damage to facilities at the Port. Repair of structural

damage to piles and foundations, shear wall retrofitting at the Ferry Building, and repair of a major liquefaction problem at one pier are all part of that effort. As a result of this earthquake, the Port authorities decided to increase seismic preparedness. The Port's priorities for improvements are based on a facility's public access use or ability to generate revenues. To some degree, buildings with tenants take some small priority over those without.



Bay Area Marine Transportation Facilities

The Port of Oakland also sustained damage from the Loma Prieta earthquake, primarily in the Middle Harbor. Liquefaction and settlement closed the truck access road to Terminals 35-38, and one of the connecting rail lines to Terminal 40 was shut down by vertical and horizontal displacement. Repairs to road surfaces were made by applying asphalt to pavement discontinuities; some permanent pavement replacement was done at private terminals. Two structures in the Middle Harbor also experienced failures when their supporting piles were broken. Equipment problems were also evident, as over twenty container cranes sustained damage. Estimates of up to $75 million have been made for damage repair at the Port. Because of this damage, management at the Port of Oakland has embraced more risk management techniques than in the past, and greater seismic standards will be instituted for any future construction.

At the Port of Richmond, liquefaction due to the Loma Prieta earthquake was minimal, and generally in undeveloped areas. The most significant problem was a rupture of a gasoline tank.

Although the release was limited by secondary containment, it resulted in a decision to shut down power temporarily as a safety measure. Damage was limited to private facilities, so owner-operators were in charge of the cost of service restoration. The newest terminal at the Port complies with current seismic codes, but all other facilities are older and probably do not. Note that the Port of Richmond, along with the Port of Redwood City, are smaller operations than those of San Francisco and Oakland, with operational responsibilities in the hands of the tenants rather than those of the ports.

The Port of Redwood City had the least amount of damage from the Loma Prieta earthquake of any Bay Area port. Although minor problems with broken water lines and piles were observed, operations were not disrupted. Damage of approximately $250,000 was estimated for the Port itself, not including repairs needed on private facilities.

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- Ben Kutnick, Director of Administration, Port of San Francisco, November 2, 1995.
- Jim Faber, Operations Manager, Port of Richmond, November 20, 1995.
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- Joe Gaidsick, Vice President, Benicia Port Terminal Co., November 14, 1995.

Rail Transportation Facilities

Introduction

Rail transportation is another critical link in the Bay Area's economy and transportation network. Rail lines move passengers and cargo both within and beyond the Bay region.

In the Bay Area, three passenger systems are used by the public. Two of these, Bay Area Rapid Transit (BART) and CalTrain, link commuters and other users to San Francisco from two distinct areas. BART carries riders from the east Bay (Alameda and Contra Costa counties), and CalTrain serves the San Francisco peninsula (San Mateo and Santa Clara counties). A third passenger system, Amtrak, connects the Bay Area to the rest of the country by either a north-south coastal route or an east-bound route. Light rail systems, used in both San Francisco and the south Bay, are considered part of the local transit system of those two communities rather than as major rail networks.

The Bay Area has historically been served by several major freight companies, the largest being Southern Pacific. These companies provided cargo transportation and domestic shipment of goods and products to and from the Bay Area. Over time, these companies consolidated services and mergers occurred, resulting in Union Pacific currently being the primary transporter of rail cargo in the region. Two other companies also are involved in Bay Area rail freight. Regardless of the number of train companies serving the region, the freight rail system is a crucial part of the region's commerce.

Rail lines can be a great asset after a natural disaster. In the event of an earthquake that results in major damage to the freeway and road network, access to railroads can offer a means of obtaining needed supplies and services. The largest apparent need for rail service is for moving people. This need is particularly true after a damaging earthquake, as people will take alternate methods of transportation if their usual method is not functioning well or at all. For example, ***following the Loma Prieta earthquake, BART temporarily expanded its capacity to carry commuters which normally used the Bay Bridge but were unable to do so while the bridge was being repaired.***

Passenger Rail Systems

The Bay Area Rapid Transit District is the largest rail transport operator in the region based on the number of yearly passengers. In 1995, 34 stations were in operation, with five more stations planned and under construction (four in the east Bay and one in San Mateo County) for opening by the beginning of 1997. An additional four stations are planned in San Mateo County for opening by the year 2000. BART's track mileage will be increasing in 1997 from 71 miles to 93 miles with the opening of the five stations under construction. An additional 8 miles of track will be added when the four San Mateo stations are complete, which include an extension to San Francisco Airport. BART's ridership averages 250,000 people per day. The BART maintenance system consists of five facilities located in Daly City, Concord, Richmond, Oakland, Hayward

which service and repair the District's 570 rail cars. Although express bus service from selected east Bay stations is part of the system, it is described in the section on "Transit Facilities."

CalTrain, providing service from San Francisco south to Gilroy, has 32 stations – four in San Francisco, 13 in San Mateo, and 15 in Santa Clara counties. The system extends 77 miles through these communities. Approximately 20,000 passengers are carried by CalTrain daily.

Amtrak has nine stations in the Bay Area, from San Jose to Suisun-Fairfield. This Bay Area segment can connect a traveler to eastern routes via the Capitol line (to Sacramento only) and the California Zephyr, or to northern (Pacific northwest) and southern (Los Angeles and San Diego) destinations via the Coast Starlight line. An alternative north-south route is the San Joaquin through the central valley. Local travel within any part of the Bay Area segment of the Amtrak system has been growing since additional stations were opened and more trains introduced.

Light Rail Systems

Light rail systems are part of the street network of two local transit systems – San Francisco's Municipal Railway, and the Valley Transportation Authority (Santa Clara County). Although these systems connect to other public transit networks, notably BART and CalTrain, they are considered as providing community level service, along with buses.

Freight

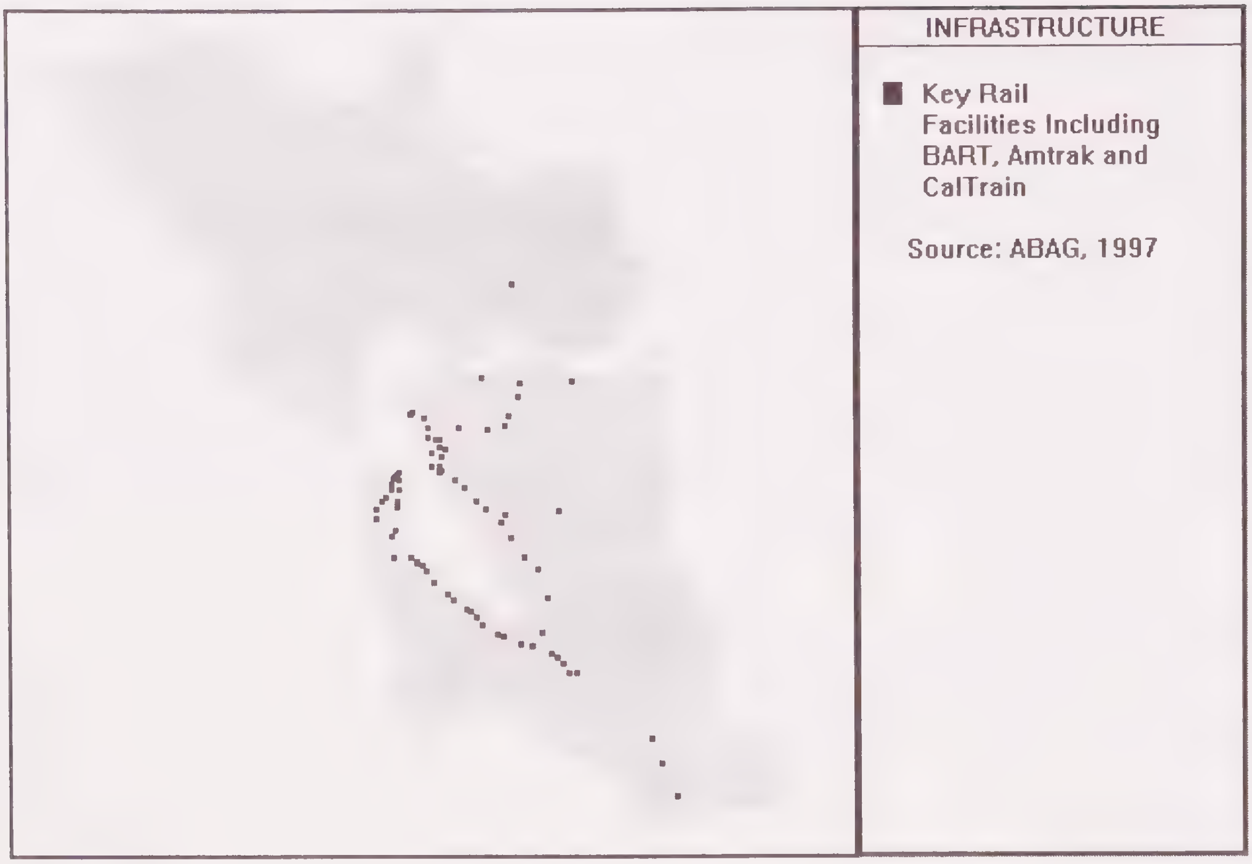
In addition to passenger systems, an important part of the network of rail service is for movement of products and materials. Transportation of goods will be crucial to the economic recovery of the Bay Area following a large earthquake. Although a small amount of the region's rail freight is carried by Amtrak, most is hauled by three railroads: Union Pacific, Southern Pacific (which will be merging with Union Pacific), and Burlington Northern Santa Fe. Three lines of these companies extend from the Bay Area – south towards Los Angeles, east to Sacramento and points north, and east to Stockton and the Central Valley. Rail freight contributes approximately 100 million dollars annually to Bay Area commerce.

Location of Rail Transportation Facilities

This map depicts 80 mapped rail passenger facilities in the Bay Area operated by BART, Amtrak, and CalTrain.

Experience in the Loma Prieta Earthquake

No significant structural damage occurred to either BART or CalTrain from the 1989 Loma Prieta earthquake.



Bay Area Rail Transportation Facilities

The BART system sustained minor damage at several of its east Bay stations, and in the transition structure on the east side of the transbay tube. Water seepage occurred in the two tubes themselves, but this was not due to any structural problems. Loss of power in San Francisco resulted in black outs at several stations in the city; more importantly, it affected sump pumps at the Powell Street station which are used to remove water that collects in an adjacent tunnel from an underground stream. The water level rose to within 2 inches of the rails before generators were obtained from the city's public works department for operating the pumps.

In addition to power loss to the stations in San Francisco, power was also lost to one of the seven substations operated by PG&E within the BART system which supply traction power for operating the trains. BART thus had difficulties moving its stopped trains to the next station on the San Francisco side of the Bay, including one in the transbay tube. Some power was transmitted to the west side of the Bay from the east Bay through the third rail to enable the stopped trains to pull ahead for safe disembarkation. All passengers detrained within 30 minutes after the earthquake. BART was then shut down because of power limitations and for system inspection. Limited service began after about 8 hours, and normal service was restored for the morning commute, twelve hours after the earthquake.

Backup systems were important to BART operations. Emergency batteries were used to provide limited lighting to San Francisco stations. In a couple of east Bay stations, temporary power loss interrupted radio communications, but train operators used backup mobile radios without problems.

As the post-earthquake recovery continued, increased patronage due to the damage to the Bay Bridge induced BART to provide 24-hour service. Ridership quickly increased about 62% over its average pre-earthquake volume. Fortunately, an expansion of BART's maintenance capacity coincided with the increased level of operations, and problems with servicing additional trains were avoided. After the Bay Bridge was reopened, ridership stabilized at an approximate 10% greater volume than before the earthquake.

For CalTrain, the only reported damage from the Loma Prieta earthquake was a few bricks falling from the inside of a tunnel. A section of tracks south of San Jose, which are not part of the CalTrain System at this time but were not in 1989, buckled; this problem was repaired within two days. As with BART, and as the law requires, all operating trains at the time of the earthquake were driven to the next station and all passengers evacuated. The system was shut down and inspected. This inspection was completed and service was resumed (at reduced speed) within five hours. Ridership also increased by approximately 32% for the month after Loma Prieta. It dropped to about 10% higher than earlier before stabilizing.

Amtrak has expanded its Bay Area service since the Loma Prieta earthquake; it had a much reduced presence in the region in 1989. Four of the nine Amtrak stations were standing at the time of the Loma Prieta earthquake, and no problems occurred with them. Similarly, no track failures were reported along the current Amtrak routes.

No evidence suggests that freight lines sustained damage enough to affect operations.

A Note on Expected BART Performance in Future Bay Area Earthquakes

The BART network was designed in the early 1960s to earthquake standards more stringent that the equivalent standards for highway construction at that time. The principal rationale was that failure of just part of the system would cripple the network. However, as part of the design of the BART extensions and following the earthquakes in Loma Prieta, Northridge and Kobe, BART re-evaluated this design standard. Although the tube from Oakland to San Francisco is not expected to experience significant damage, the elevated track and the fault crossings will be heavily damaged. BART currently is seeking funding to upgrade each of the 1,700 supports on the 25 miles of older elevated track. The average cost of these upgrades is expected to be approximately \$100,000 per support, or a total of \$170 million. BART has stockpiled equipment and supplies to repair the fault crossings. Two of those crossings (on the newer lines) were designed to occur at grade on dirt. Repair of these sections is expected to occur within several days because BART was able to repair the 250 - 300 feet of tract warped in the Oakland Hills fire in about one week. However, because the tunnel bores are only several inches larger than needed at the Hayward fault crossing on the Concord-Oakland line, any significant fault offset will require that portions of these tunnels be rebored. (Thus, the tunnel bores were designed one foot

larger than needed in radius to accommodate on-going creep, not the fault rupture associated with a major earthquake.) Finally, the BART headquarters building is of a type of construction known to experience failure when exposed to violent ground shaking. The computer equipment for operating the entire BART network is located adjacent to the basement of that office building. A new building is currently planned for occupancy in 2001.

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Transit Facilities

Introduction

Public transportation systems operating on the street network of cities and counties are primarily buses. A few agencies may also offer light rail and ferry transport. (Note that the bus and associated maintenance facilities of BART are included in this discussion.)

The maintenance and service facilities of the transit agencies in the region are another critical link in the region's response to a natural disaster. Extra buses and rail cars will need to be dispatched, as well as vehicles refueled, maintained, and/or repaired. These sites are sometimes known as "corporation yards." Expanded or emergency service, as well as regular service, would not be possible without such facilities.

Buses

In the Bay Area, several agencies handle much of the transit load. These all have bus service, and include:

- Golden Gate Transit, with ferries (Marin and Sonoma Counties)
- San Francisco Municipal Railway, with trolleys, rail, and cable cars
- AC Transit (Alameda County)
- CCCTA (Central Contra Costa County Transit Authority)
- SamTrans (San Mateo County Transit District)
- SCCTD (Santa Clara County Transit District), with light rail
- Vallejo Transit, with a ferry (part of Solano County)
- BART

Golden Gate Transit District has three facilities located in San Rafael, Novato, Santa Rosa. These provide maintenance, fueling, and storage services for the District's fleet of buses.

Within the City of San Francisco, seven facilities provide similar services for the vehicles of the San Francisco Muni Railway. This agency has 893 buses (345 trolleys, 438 diesels, 100 articulated coaches, and 10 historical streetcars). In addition, it operates 33 cable cars. One of the seven maintenance facilities is exclusively used for cable car servicing. The yards also house 143 service vehicles (trucks, vans, pickups, forklifts, tractors, etc.), 67 of which are equipped with mobile radios.

In the east Bay, the five facilities serving AC Transit are located in Emeryville, Richmond, Oakland, east Oakland, and Hayward. The number of buses serviced, fueled, and stored at these garages and maintenance yards totals 719.

Contra Costa County Transit Authority has one maintenance and storage yard, located in Concord.

SamTrans, servicing San Mateo County, uses four facilities. Two of them are District owned (South San Francisco and San Carlos). The other two are run by contractors for the District (in San Francisco and Redwood City).

Santa Clara County Transit District operates three facilities – two in San Jose and one in Mountain View. The bus fleet totals 464 vehicles.

The Vallejo Transit District has one facility, in Vallejo, which houses 49 buses and a small fleet of maintenance vehicles.

BART contracts with one of the above transit agency for express bus service and maintenance and does not maintain its own bus facilities. Its contracts are not long term, and the agency supplying service has changed over time.

Light Rail

Light rail vehicles are operated by two agencies – S.F. Municipal Railway and Santa Clara County Transit. In San Francisco, one facility services the 130 light rail vehicles of the agency (on Geneva Avenue). Santa Clara County Transit's rail yard is located in San Jose for the 50 rail vehicles which make up its system.

Park and Ride Facilities

In an attempt to encourage transit use and carpooling, Park & Ride lots have been constructed in every county in this region except San Francisco. There are a total of 140 lots in these nine counties, as shown below.

TABLE 27: Number of Park and Ride Lots by County

Alameda	Contra Costa	Marin	Napa	San Mateo	Santa Clara	Solano	Sonoma	Santa Cruz
20	26	14	1	12	33	13	17	4

Of these lots, however, 18 are shared or are for the exclusive use of other transit agencies: BART (7 lots), Golden Gate Ferry (1), or Santa Clara County Transportation Agency (10).

The general lots have a total of 8,879 spaces. When combined with the partially-restricted lots, which contain 10,685 spaces, there are a total of 19,564 spaces available for commuters. This does not count regular BART lots.

Location of Transit Facilities

This map depicts 181 mapped transit facilities in the Bay Area, including:

- 35 truck and bus maintenance yards
- 146 park and ride lots

Specific Planning Considerations

Northern Hayward Earthquake

Roads

- All roads crossing faults will probably close. For example, Highways 13 and I-580, which run parallel to the fault source and even cross the fault, will be affected by this earthquake. I-80 crosses the fault source near San Pablo north of the I-580 junction, while Highway 24 crosses it near the Caldecott Tunnel. Many highways and roads near the fault are also vulnerable to landsliding, causing additional closures.
- Roads in the I-880 and I-80 corridors will experience road closures due to shaking, liquefaction and building damage.
- BART will probably be unable to pick up extra service due to extensive damage to the supports for its elevated sections, and may even contribute to blocking of roadways and highways.
- Local roads and highways in the Highway 101 corridor, particularly near I-580 and the Richmond-San Rafael Bridge and near State Route 37, as well as in San Francisco, are also expected to experience multiple road closures.
- Emergency planners should consider pre-designating alternative north-south emergency arterials between the heavily impacted Bay shoreline and the fault source.

Bridges

- From an emergency planning perspective, this scenario earthquake is particularly problematic because ***all*** of the Bay Area's toll bridges may be affected, either directly or due to closures of local roads feeding the bridges. The San Francisco-Oakland Bay and San Mateo Bridges are particularly subject to problems in this earthquake. Even if these bridges remain intact, liquefaction and extensive settlement on the approaches may impact traffic flow.
- In addition, non-retrofitted local roadway bridges on local roads should be considered a weak link along transportation routes.

Airports

- The Oakland International Airport is expected to be affected by multiple road closures servicing its facilities.
- The San Francisco and San Jose International Airports, as well as Moffett Field and other smaller airports such as San Carlos and Hayward, may be more accessible than Oakland. Therefore, these airports should plan for increased air and vehicle traffic, both immediately and long term, following this earthquake.

Ports

- The Ports of Oakland, San Francisco, and Richmond are expected to be affected by road closures after this earthquake. Oakland's facilities for large container ships are non-redundant in the immediate Bay Area. The Port of Kobe, Japan, experienced similar impacts following the Hyogo-Ken Nanbu earthquake in 1995. These facilities may be able to unload ships but not transport cargo out of the impacted area immediately following this earthquake.
- Ports in southern California and along the entire west coast may experience increased shipping traffic should these ports be heavily impacted by an earthquake.

Southern Hayward Earthquake Impacts

The Scenario

This scenario earthquake is for a magnitude 7.0 earthquake on the southern segment of the Hayward fault between southern Oakland and the border of Alameda and Santa Clara counties.

Distribution of Closures

An earthquake along the southern segment of the Hayward fault would cause approximately ***809 road closures***. Almost three quarters of these (74%) are expected to occur within Alameda County alone. Santa Clara County, which is located at the southern tip of the fault, is only expected to experience 69 closures, merely 9% of the total. This situation is best explained by the significantly lower density of the northern portion of this county than Alameda County.

Fault rupture is expected to be one of the most significant causes of road closures: approximately one third of the total road closures in this scenario are expected to be generated by fault rupture and all of them are expected to occur within Alameda County.

TRANSPORTATION SYSTEM CLOSURES DUE TO AN EARTHQUAKE ON THE SOUTHERN SEGMENT OF THE HAYWARD FAULT

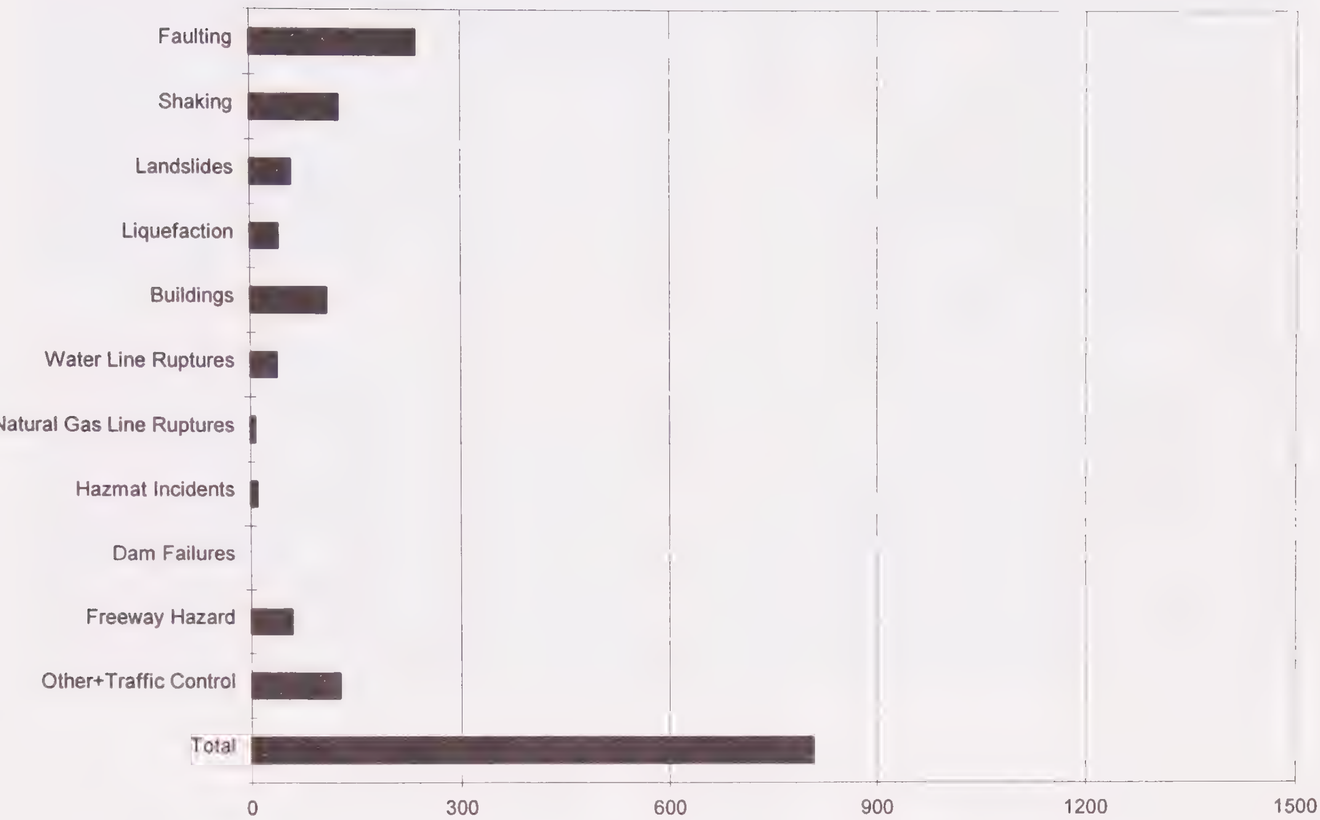
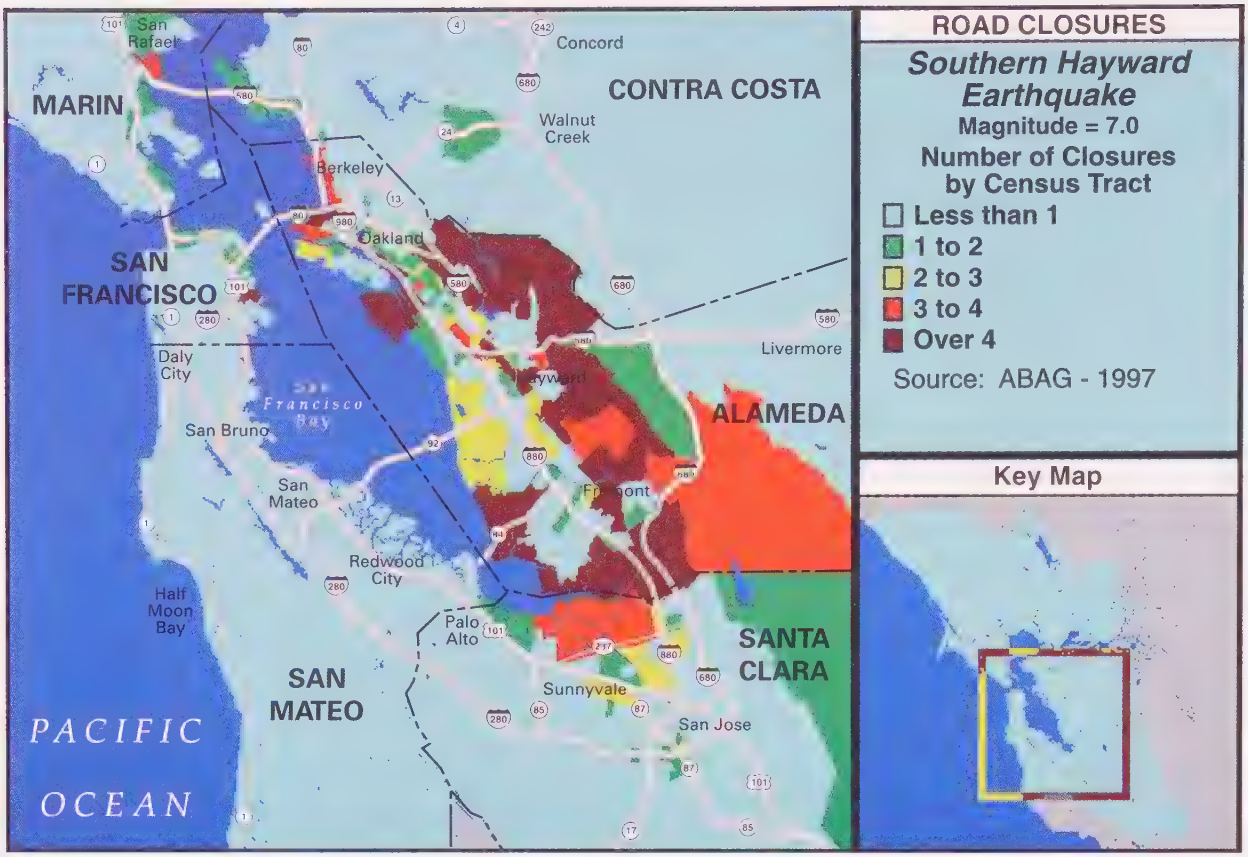


TABLE 35: Transportation System Closures by Hazard Type and County

Hazard Type	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	TOTAL
Faulting	236	0	0	0	0	0	0	0	0	236
Shaking	83	7	7	0	3	3	23	0	0	126
Landsliding	31	8	5	0	2	2	8	1	1	58
Liquefaction	12	4	10	0	7	1	1	3	2	40
Buildings	70	2	1	0	31	0	5	0	0	109
Water Line Ruptures	25	2	1	0	1	0	7	0	0	38
Natural Gas Line Ruptures	5	0	0	0	0	0	1	0	0	8
Hazmat Incidents	8	0	0	0	0	0	1	0	0	10
Dam Failures	0	0	0	0	0	0	0	0	0	0
Freeway Hazard	38	3	3	0	1	1	11	0	0	58
Other	94	5	5	0	9	1	11	1	1	126
TOTAL	602	31	31	1	55	9	69	7	4	809



Concentrations of Closures and General Planning Implications

As can be seen from examining the above map, most of the closures are expected to occur along the southern portion of the east Bay. The zones that are expected to have the most severe disruptions are located adjacent to the fault along the Highway 580 and 238 corridors, and along segments of the 880 corridor. While these north-south connectors may not be fully operational, there should be available alternatives through the local street network.

While it has not been within the scope of this project to predict the performance of individual structures or facilities, the effect on the Bay Area's toll bridges is expected to be serious. In addition, the devastating effect to the transportation system in and around critical transportation facilities such as the Oakland airport should be considered for post disaster planning.

Specific Planning Considerations — Southern Hayward Earthquake

Roads

- I-580, which runs parallel to the fault source and even crosses the fault, will be affected by this earthquake. Many highways and roads near the fault source are also susceptible to landsliding.
- Roads in the Highway 13, 24, I-880 and I-80 corridors will experience closures due to shaking, liquefaction and building damage.
- BART will probably be unable to pick up extra service due to extensive damage to the supports for its elevated sections, and may even contribute to blocking of roadways and highways.
- Local roads and highways in the Highway 101 corridor, particularly near the junctions with the Richmond-San Rafael Bridge and in San Francisco, may experience multiple road closures.
- Emergency planners should consider pre-designating alternative north-south emergency arterials.

Bridges

- From an emergency planning perspective, this earthquake is particularly problematic because ***all*** of the Bay Area's toll bridges may be affected, either directly or due to closures of local roads feeding the bridges. The Bay, San Mateo, and Dumbarton Bridges are particularly subject to problems in this earthquake. Even if these bridges remain intact, liquefaction and extensive settlement on the approaches may impact traffic flow.
- In addition, non-retrofitted local roadway bridges on local roads should be considered a weak link along transportation routes.

Airports

- The Oakland International Airport is expected to be affected by multiple road closures servicing its facilities.
- The San Jose International and Hayward airports, while not experiencing quite as many closures as Oakland, will probably still be affected by a few closures on local roads.
- The San Francisco International Airport and Moffett Field are expected to be more accessible than either Oakland or San Jose. Therefore, these airports should plan for increased air and vehicle traffic, both immediately and long term, should Oakland and San Jose International be impacted. Facilities at Livermore and Concord's Buchannan Field will also be useful.

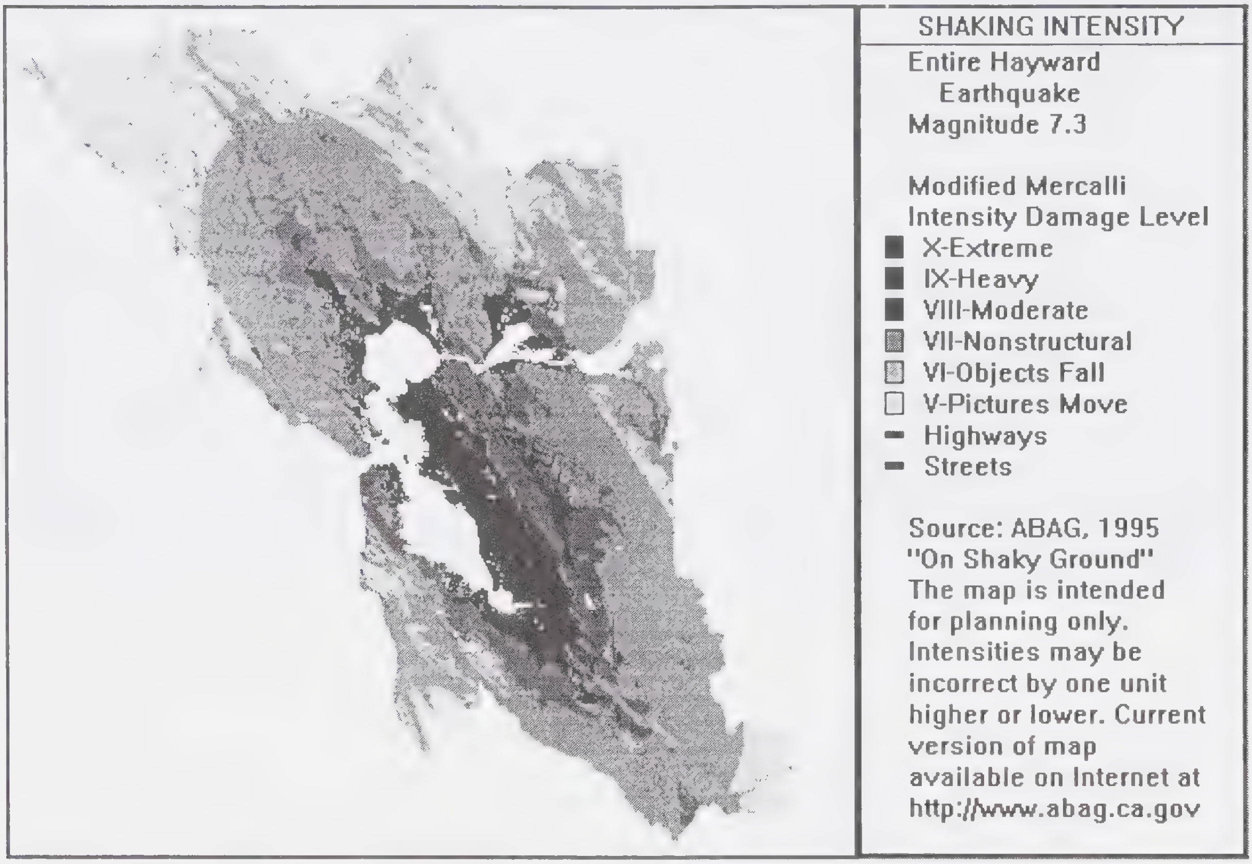
Ports

- The Ports of Oakland and San Francisco are expected to be affected by road closures after this earthquake, and the Richmond and Benicia ports may also be disrupted. Oakland's facilities for large container ships are non-redundant in the immediate Bay Area. The Port of Kobe, Japan, experienced similar impacts following the Hyogo-Ken Nanbu earthquake in 1995. These facilities may be able to unload ships but not transport cargo out of the impacted area after the earthquake.
- Ports in southern California and along the entire west coast may experience increased shipping traffic should these ports be heavily impacted by an earthquake.

Hayward Earthquake -- Entire Length - Impacts

The Scenario

This scenario earthquake is for a magnitude 7.3 earthquake on the entire length of the Hayward fault from San Pablo Bay to the border of Alameda and Santa Clara counties.



Distribution of Closures

An earthquake along the entire Hayward fault would cause approximately ***1,484 road closures*** and would have the most devastating effect out the eleven scenarios modeled in this report. Almost three fifths of the expected closures (57%) are expected to occur within Alameda County alone. Contra Costa and San Francisco counties are expected to be the next most severely affected areas. In combination, these two counties are expected to account for approximately one third (31%) of the total closures.

The type of closures within Alameda and Contra Costa counties include the direct hazards of fault rupture, shaking and landsliding. Closures within San Francisco can be attributed to its older and denser urban pattern.

TRANSPORTATION SYSTEM CLOSURES DUE TO AN EARTHQUAKE ON THE ENTIRE LENGTH OF THE HAYWARD FAULT

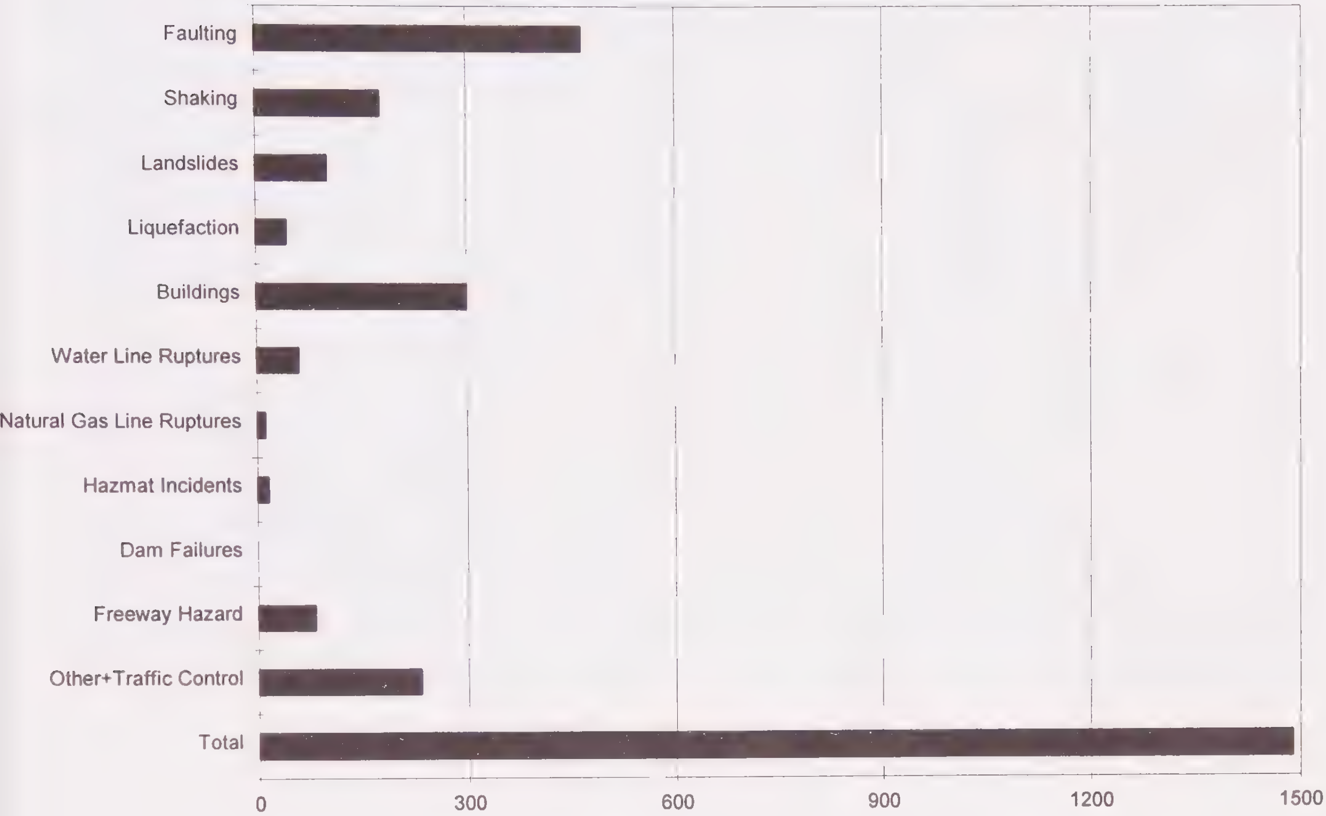
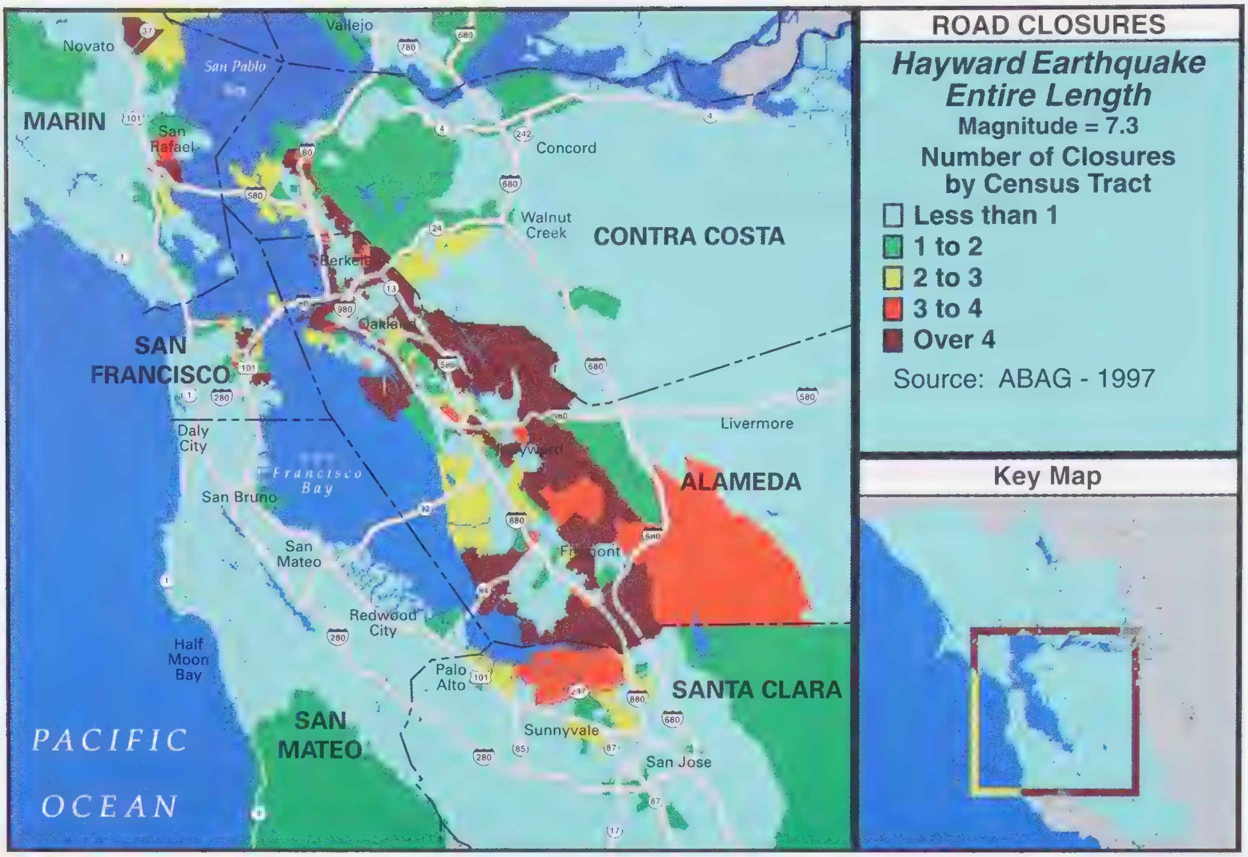


TABLE 36: Transportation System Closures by Hazard Type and County

Hazard Type	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	TOTAL
Faulting	353	113	0	0	0	0	0	0	0	466
Shaking	103	21	14	0	6	5	26	0	1	177
Landsliding	42	21	9	1	4	5	11	2	5	101
Liquefaction	12	4	10	0	9	1	1	4	2	44
Buildings	114	9	1	0	167	1	5	2	0	300
Water Line Ruptures	31	11	2	0	2	1	10	1	2	60
Natural Gas Line Ruptures	6	2	0	0	0	0	2	0	0	12
Hazmat Incidents	10	2	1	0	1	0	1	0	0	16
Dam Failures	0	0	0	0	0	0	0	0	0	0
Freeway Hazard	47	9	7	0	3	2	12	0	1	81
Other	133	36	8	0	36	3	13	2	2	232
TOTAL	851	227	52	3	228	19	79	12	14	1484



Concentrations of Closures and General Planning Implications

As can be seen from examining the above map, most of the closures are expected to occur along critical transportation corridors. In the east Bay the zones that are expected to have the most severe disruptions are located adjacent to the fault along I-580 and State Route 238 corridors, and along large portions of the I-880 corridor. While these north-south connectors may not be fully operational, there should be available alternatives through the local street network.

Disruptions to the local street network are expected to occur within San Francisco itself and, as in the east Bay, they are expected to be concentrated along some critical connectors such as along Interstates 80 and 280.

At the same time, while significant disruptions are expected both within the east Bay and within San Francisco, the effect on the Bay Area's toll bridges is expected to be serious. This situation is particularly critical since in most cases these bridges are not redundant.

Specific Planning Considerations — Hayward Earthquake - Entire Length

Roads

- Highways 13 and I-580, which run parallel to the fault source and even cross the fault, will be affected by this earthquake. I-80 also crosses the fault source near San Pablo north of the I-580 junction. Many highways and roads near the fault source are also susceptible to landsliding.
- Roads in the I-880 and I-80 corridors will experience road closures due to shaking, liquefaction and building damage.
- BART will probably be unable to pick up extra service due to extensive damage to the supports for its elevated sections, and may even contribute to blocking of roadways and highways.
- Roads and highways in the Highway 101 corridor, particularly near the Richmond-San Rafael Bridge and State Route 37, as well as in San Francisco, are expected to experience multiple closures.
- Emergency planners should consider pre-designating alternative north-south emergency arterials between the heavily impacted Bay shoreline and the fault source.

Bridges

- From an emergency planning perspective, this earthquake is particularly problematic because ***all*** of the Bay Area's toll bridges may be affected, either directly or due to closures of local roads feeding the bridges. The Richmond-San Rafael, Bay, San Mateo, and Dumbarton Bridges are particularly subject to problems in this earthquake. Even if these bridges remain intact, liquefaction and extensive settlement on the approaches may impact traffic flow.
- In addition, non-retrofitted local roadway bridges on local roads should be considered a weak link along transportation routes.

Airports

- The Oakland and San Francisco International Airports are expected to be affected by multiple road closures servicing their facilities.
- The San Jose International Airport, Hayward Airport, and Moffett Field, while not experiencing quite as many closures as Oakland, will probably still be affected by several closures.
- Travis Air Force Base would be the closest airfield capable of handling large commercial and cargo jets should all of the above airports be inaccessible. Therefore, this airport should plan for increased air and vehicle traffic, both immediately and long term.

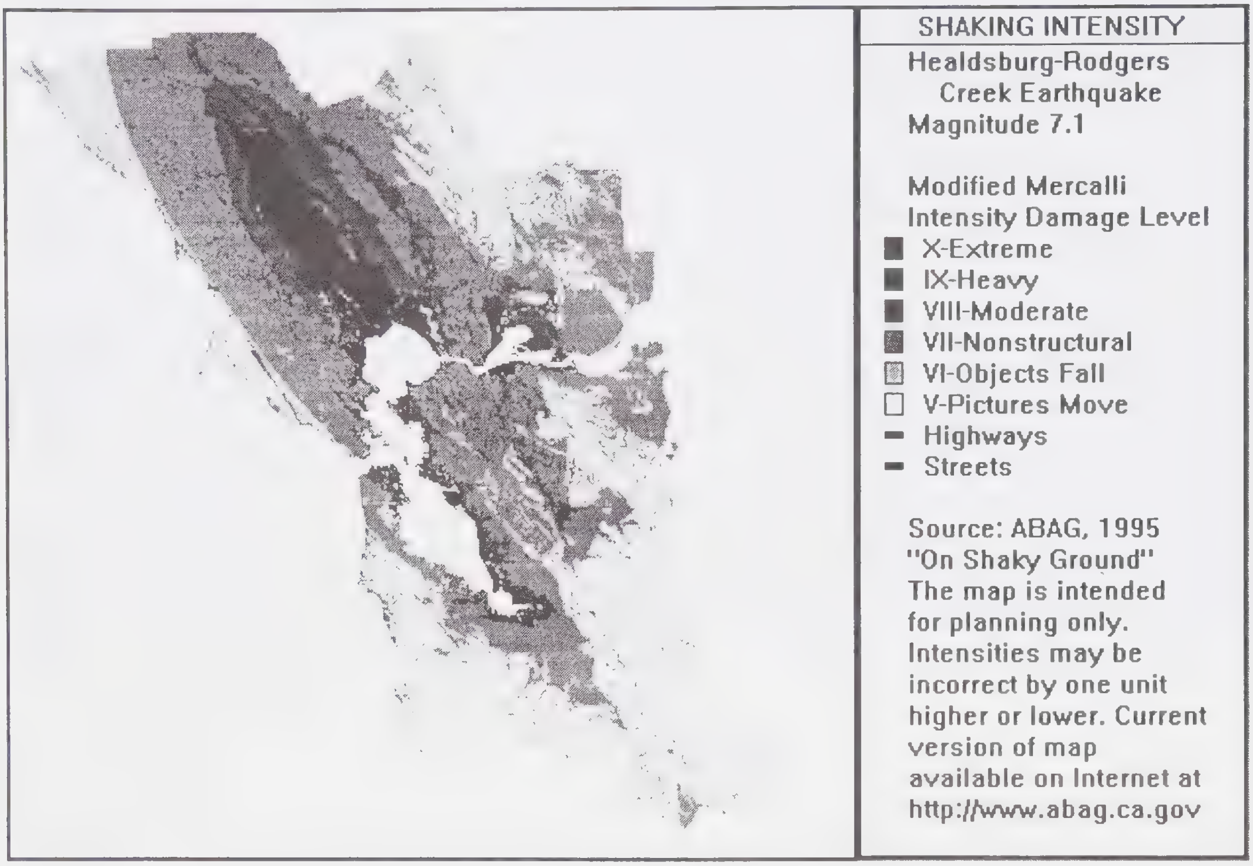
Ports

- The Ports of Oakland and San Francisco are expected to be affected by road closures after this earthquake. Oakland's facilities for large container ships are non-redundant in the immediate Bay Area. The Port of Kobe, Japan, experienced similar impacts following the Hyogo-Ken Nanbu earthquake in 1995. These facilities may be able to unload ships but not transport cargo out of the impacted area.
- Ports in southern California and along the entire west coast may experience increased shipping traffic should these ports be heavily impacted by an earthquake.

Healdsburg-Rodgers Creek Earthquake Impacts

The Scenario

This scenario earthquake is for a magnitude 7.1 earthquake on the Healdsburg-Rodgers Creek fault in Sonoma County.



Distribution of Closures

An earthquake along the entire Healdsburg-Rodgers Creek fault would cause approximately ***354 road closures***. Compared to the rest of the eleven scenarios modeled in this report, the Healdsburg-Rodgers Creek ranks fifth in the number of road closures.

Half of the forecasted closures are expected to occur within Sonoma County while Alameda, Marin and San Francisco counties are expected to account for almost two fifths (38%) of the total.

The type of closures within Sonoma County include the direct hazards of fault rupture, shaking and landsliding. Closures within San Francisco can be attributed to its older and denser urban pattern.

TRANSPORTATION SYSTEM CLOSURES DUE TO AN EARTHQUAKE ON THE HEALDSBURG-RODGERS CREEK FAULT

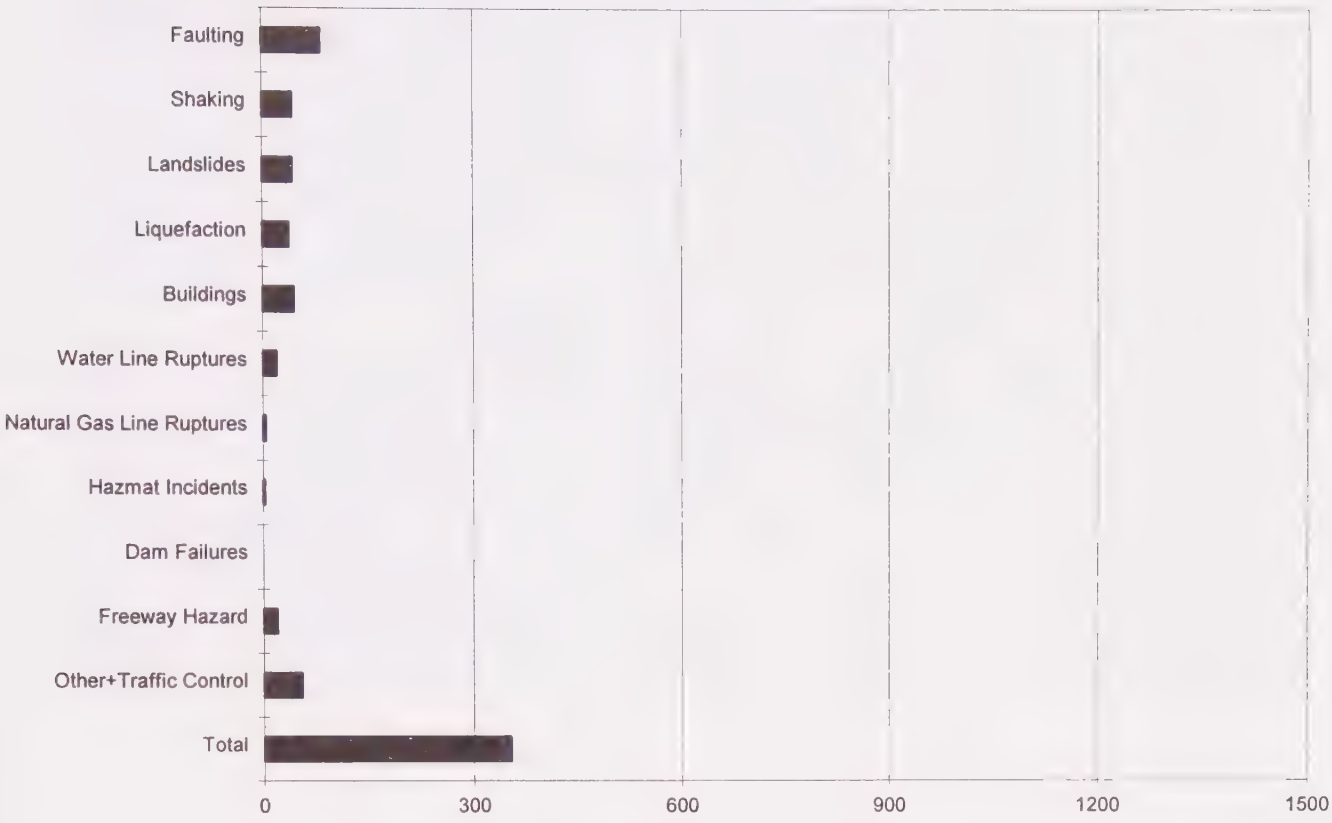
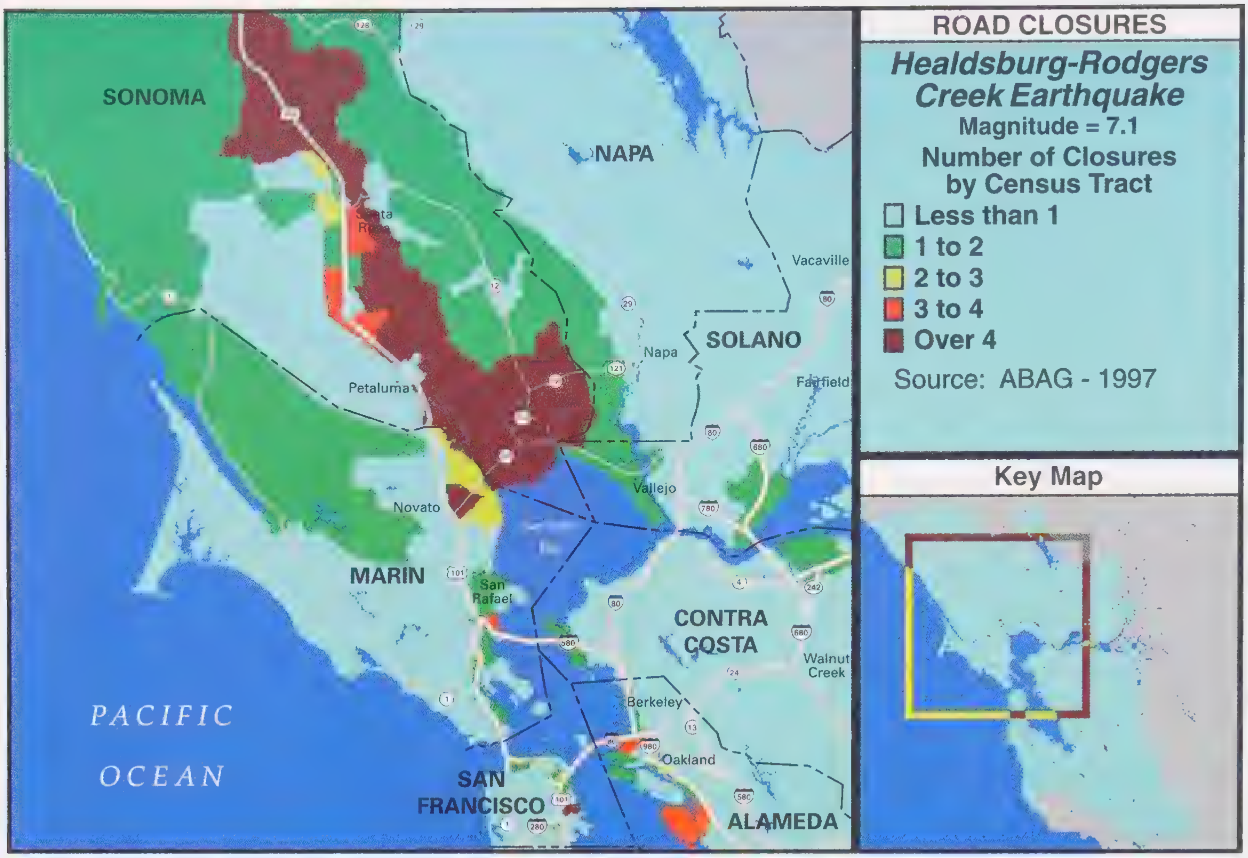


TABLE 37: Transportation System Closures by Hazard Type and County

Hazard Type	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	TOTAL
Faulting	0	0	0	0	0	0	0	0	83	83
Shaking	10	4	10	0	3	1	1	0	13	43
Landsliding	4	6	6	2	2	1	0	1	21	43
Liquefaction	11	4	10	0	6	0	0	4	2	38
Buildings	5	1	1	0	30	0	0	0	8	45
Water Line Ruptures	1	1	1	0	1	0	0	1	14	20
Natural Gas Line Ruptures	0	0	0	0	0	0	0	0	3	4
Hazmat Incidents	0	0	0	0	0	0	0	0	2	3
Dam Failures	0	0	0	0	0	0	0	0	0	0
Freeway Hazard	5	2	5	0	1	0	1	0	6	20
Other	7	3	6	1	8	1	0	1	28	55
TOTAL	43	22	40	4	51	4	3	9	178	354



Concentrations of Closures and General Planning Implications

As can be seen from examining the above map, most of the closures are expected to occur along critical transportation corridors. Significant transportation disruptions are expected along State Routes 101, 121, 116, 37 and 12. It is important to note that these roads are not redundant and that access to some of the rural communities along them might be severely impaired.

At the same time, while disruptions are expected both within the east Bay and within San Francisco, the effect on the Bay Area's toll bridges is expected to be serious. This situation is particularly critical since in most cases these bridges are not redundant.

Specific Planning Considerations

Healdsburg-Rodgers Creek Earthquake

Roads

- Highway 101 is the only major route that accesses Sonoma County from outside areas, and the only major north-south route for local traffic. Multiple closures are expected along this route. These closures are of particular concern due to the lack of alternative arterials.
- State Routes 37, 116, and 121 are also expected to experience multiple road closures, affecting both north-south and east-west movement.

Bridges

- The Carquinez, Benicia-Martinez, Richmond-San Rafael, Golden Gate, and Bay Bridges are key links between the heavily impacted areas in the North Bay and the remainder of the region, including the urban areas of San Francisco and Oakland. For planning purposes, it should be assumed that these bridges may be closed, at least for a few days. Emergency planners should expect that approaches to these bridges, as well as local roads feeding the bridges, will be affected by multiple road closures on at least one of their ends.
- The San Mateo and Dumbarton Bridges may also be affected by this earthquake.
- In addition, non-retrofitted local roadway bridges on local roads should be considered a weak link along transportation routes.

Airports

- The Oakland International Airport, as well as the smaller Sonoma and Napa airports, are expected to be affected by multiple road closures servicing its facilities.
- Travis AFB and Concord's Buchanan Field may become the closest major airfields capable of handling commercial and cargo jets. Travis becomes critical if road access from the south is heavily disrupted. Therefore, this airport should plan for increased air and vehicle traffic, both immediately and long term, following this scenario earthquake.

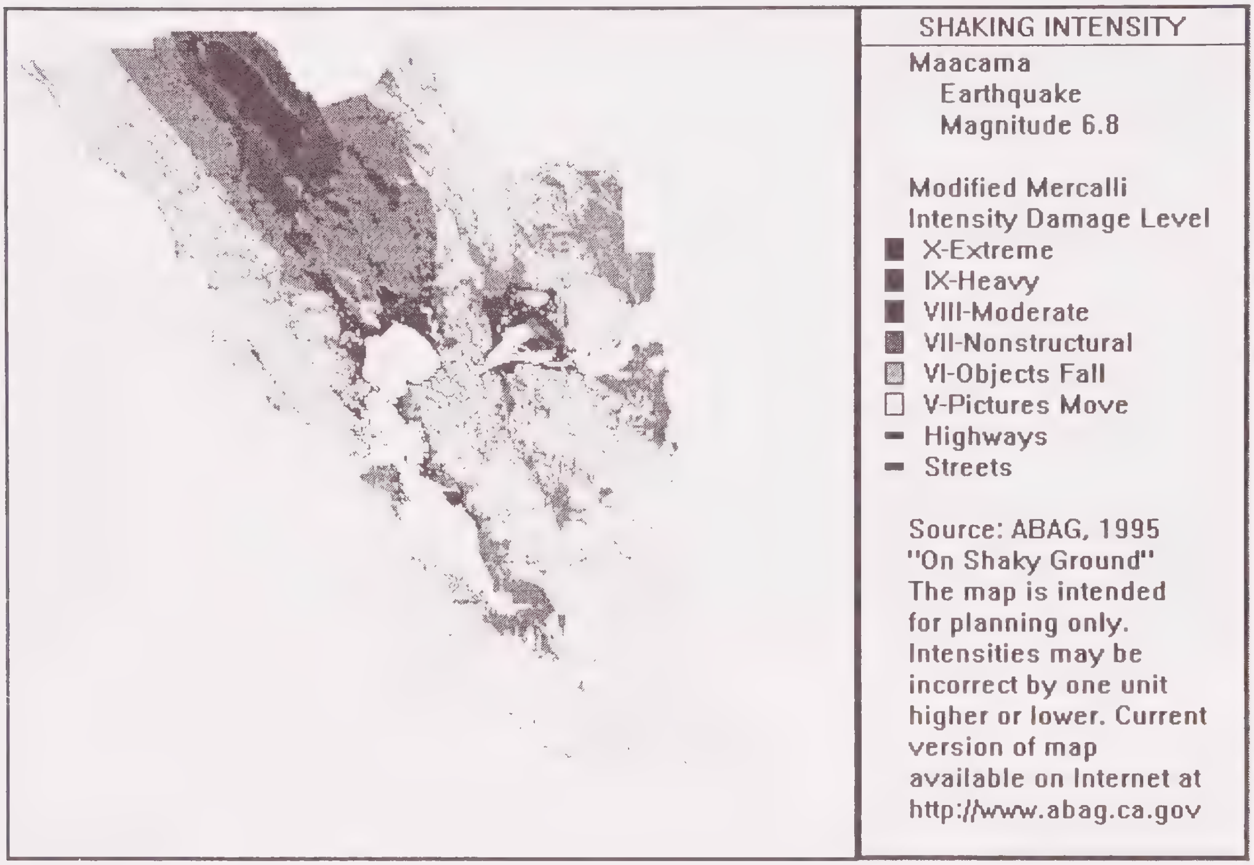
Ports

- The Ports of Oakland, San Francisco, Richmond and Benicia are all expected to be affected by road closures after this earthquake. Oakland's facilities for large container ships are non-redundant in the immediate Bay Area. The Port of Kobe, Japan, experienced similar impacts following the Hyogo-Ken Nanbu earthquake in 1995. These facilities may be able to unload ships but not transport cargo out of the impacted area after the earthquake.
- Ports in southern California and along the entire west coast may experience increased shipping traffic should these ports be heavily impacted by an earthquake.

Maacama Earthquake Impacts

The Scenario

This scenario earthquake is for a magnitude 6.8 earthquake on the Maacama fault in Sonoma County.



Distribution of Closures

An earthquake along the Maacama fault would cause approximately ***69 road closures.*** Of the eleven scenarios modeled in this report, an earthquake on this fault would generate the least number of transportation disruptions.

Two thirds of the expected closures (67%) are expected to occur within Sonoma County alone while the rest of the closures are relatively evenly distributed among the remaining eight Bay Area counties.

Fault rupture and landsliding account for approximately two thirds (65%) of the closures within Sonoma County.

TRANSPORTATION SYSTEM CLOSURES DUE TO AN EARTHQUAKE ON THE MAACAMA FAULT

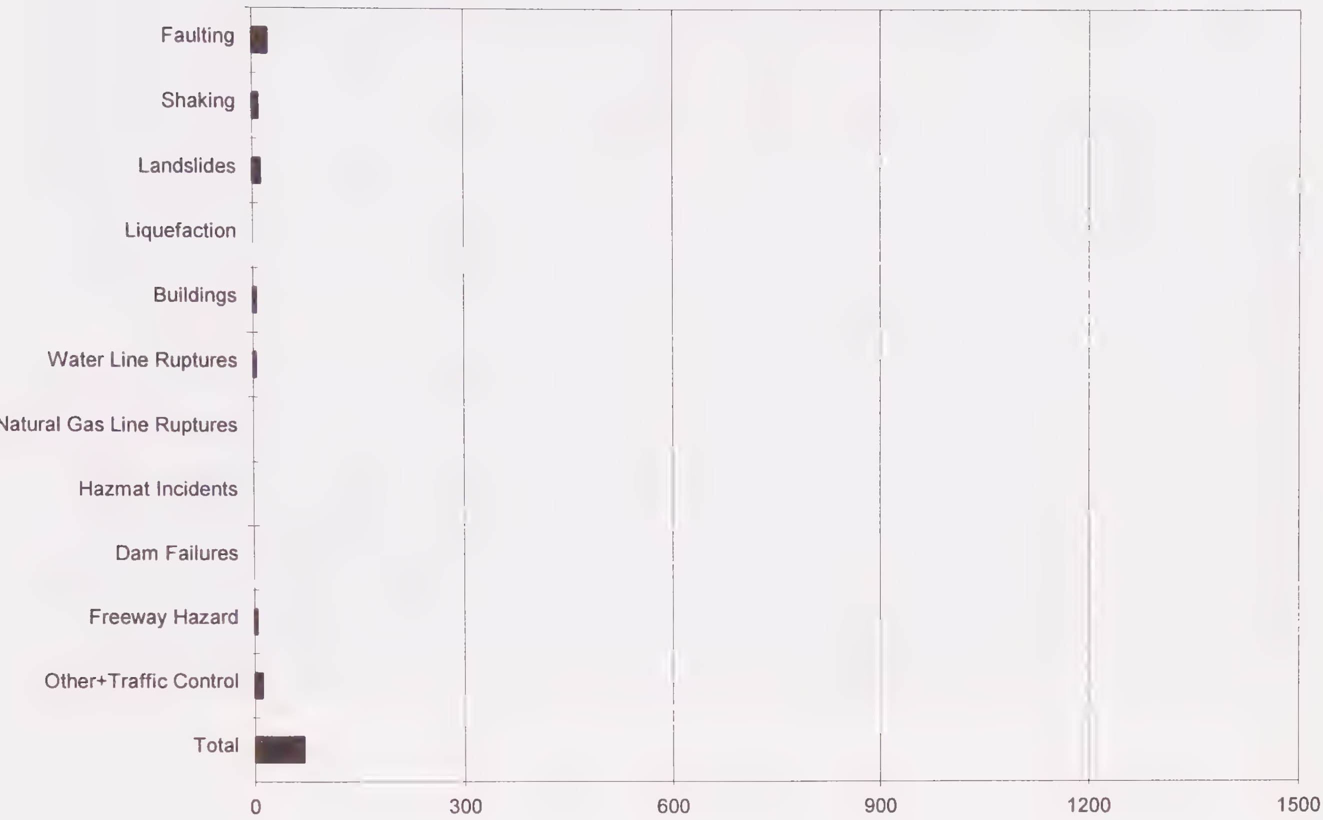
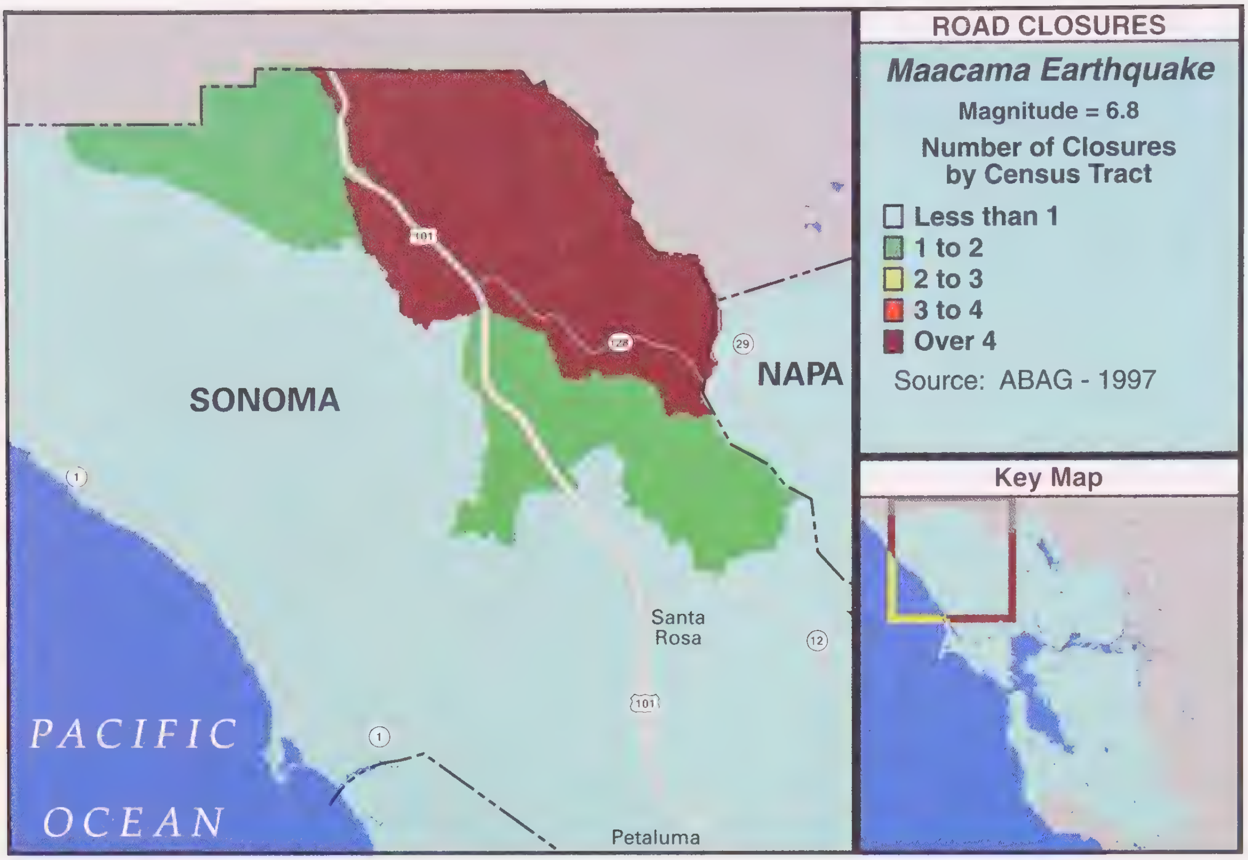


TABLE 38: Transportation System Closures by Hazard Type and County

Hazard Type	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	TOTAL
Faulting	0	0	0	0	0	0	0	0	22	22
Shaking	3	1	2	0	1	0	1	0	2	9
Landsliding	0	1	0	2	1	0	0	0	8	12
Liquefaction	0	0	0	0	0	0	0	0	1	1
Buildings	1	0	0	0	3	0	0	0	1	5
Water Line Ruptures	0	0	0	0	0	0	0	0	3	4
Natural Gas Line Ruptures	0	0	0	0	0	0	0	0	1	1
Hazmat Incidents	0	0	0	0	0	0	0	0	0	1
Dam Failures	0	0	0	0	0	0	0	0	0	0
Freeway Hazard	1	0	1	0	0	0	0	0	1	4
Other	1	0	1	0	1	0	0	0	7	11
TOTAL	6	3	4	2	6	1	1	1	46	69



Concentrations of Closures and General Planning Implications

As can be seen from examining the above map, most of the closures are expected to occur along transportation corridors. Transportation disruptions are expected within and around the communities of Healdsburg and Geyserville and along State Routes 101 and 128.

While this area presents large census tracts due to its rural nature, roads connecting the communities in this area are few. In most cases, these roads are not redundant and access to some of the rural communities along them might be severely impaired.

Specific Planning Considerations

Maacama Earthquake

Roads

- Highway 101 and State Route 128 are expected to be affected by multiple road closures as a result of this scenario earthquake. These closures are of particular concern due to the lack of alternative arterials.
- State Route 12 and other highways and local roads further to the south are not expected to be impacted significantly.

Bridges

- It is unlikely that any of the toll bridges will be affected by road closures as a result of this earthquake.
- However, non-retrofitted local roadway bridges on local roads should be considered a weak link along transportation routes.

Airports

- It is unlikely that any major or local airports will be affected by significant road closures as a result of this scenario earthquake.

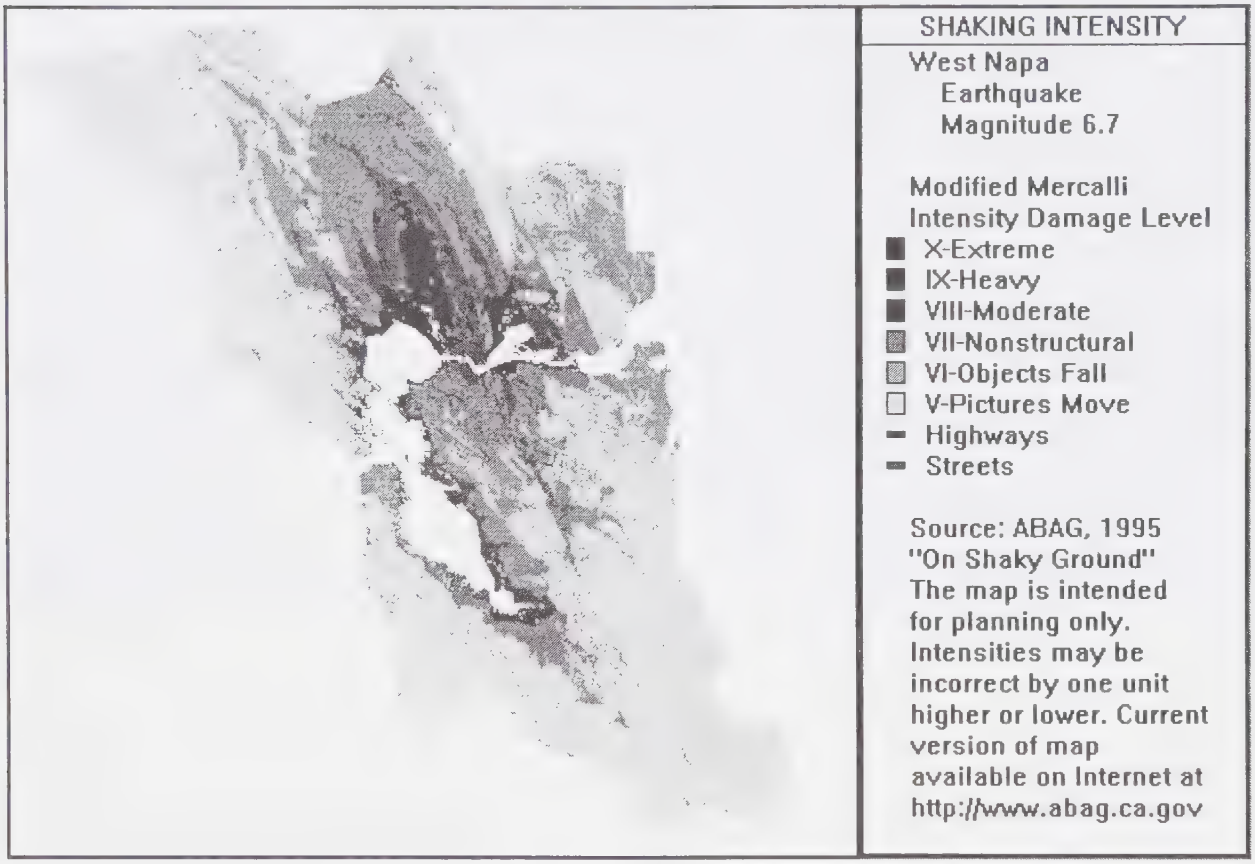
Ports

- It is unlikely that any port facilities will be affected by significant road closures as a result of this scenario earthquake.

West Napa Earthquake Impacts

The Scenario

This scenario earthquake is for a magnitude 6.7 earthquake on the West Napa fault in Napa County.



Distribution of Closures

An earthquake along the West Napa fault would cause approximately ***140 road closures.*** Of the eleven scenarios modeled in this report, an earthquake on this fault ranks ninth in the total number of closures it generates.

Exactly half of the total closures are expected to occur within Napa County alone while approximately one third (36%) are expected to occur in Alameda, Contra Costa and Solano counties. The rest of the closures are relatively evenly distributed among the remaining five Bay Area counties.

The direct hazards of fault rupture, shaking and landsliding account for approximately two thirds (69%) of the closures within Napa County.

TRANSPORTATION SYSTEM CLOSURES DUE TO AN EARTHQUAKE ON THE WEST NAPA FAULT

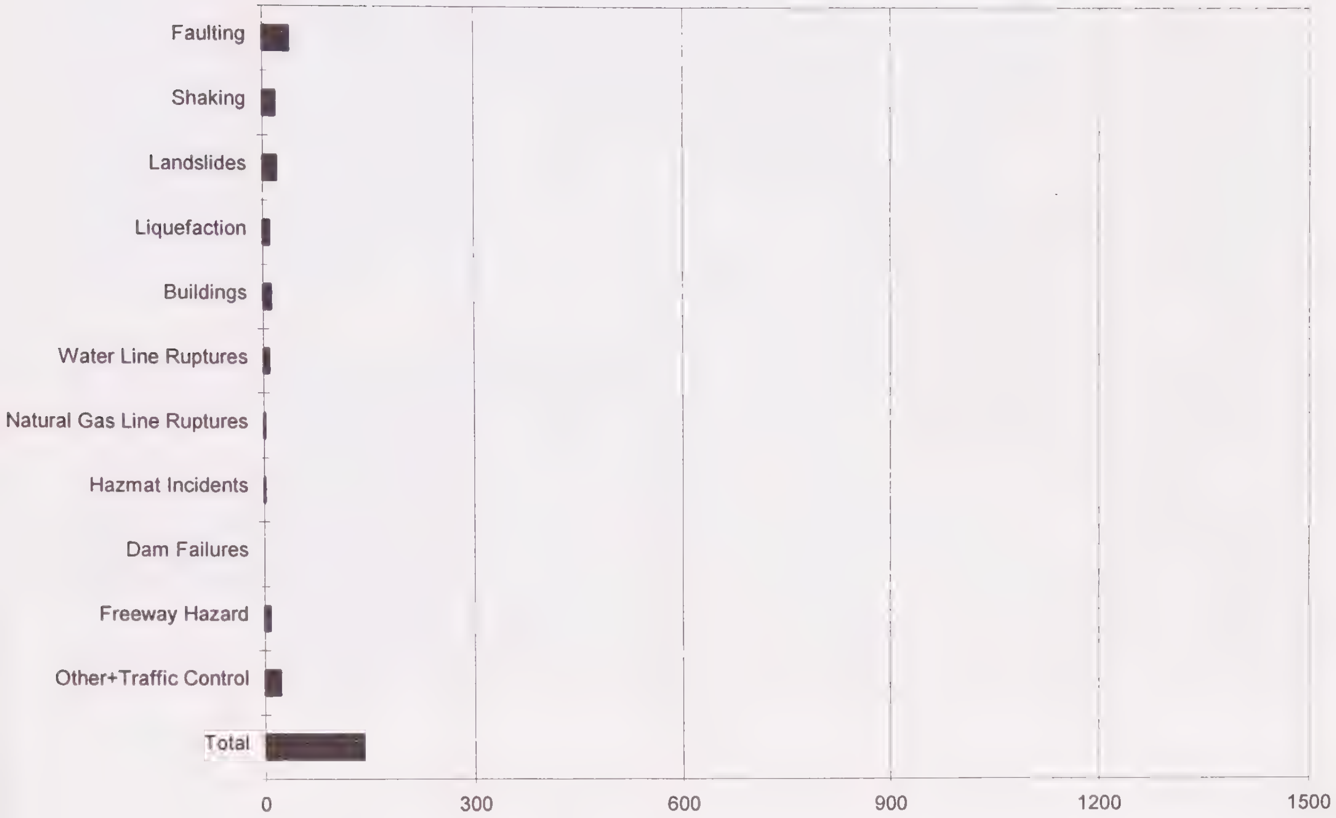
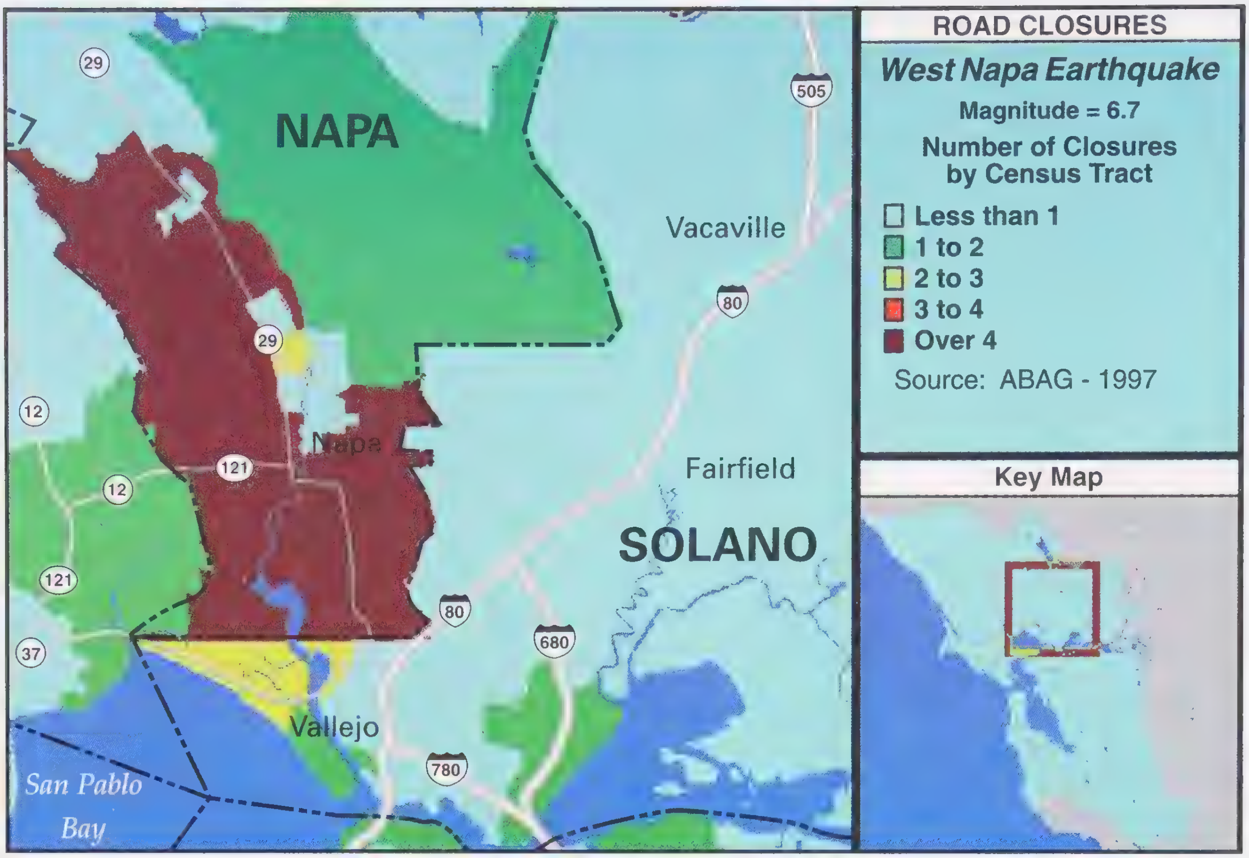


TABLE 39: Transportation System Closures by Hazard Type and County

Hazard Type	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	TOTAL
Faulting	0	0	0	38	0	0	0	0	0	38
Shaking	5	4	2	4	1	1	1	0	0	18
Landsliding	2	5	0	6	1	0	0	3	2	20
Liquefaction	1	3	0	0	0	0	0	4	1	10
Buildings	2	2	0	2	3	0	0	2	0	12
Water Line Ruptures	0	1	0	4	0	0	0	2	0	8
Natural Gas Line Ruptures	0	0	0	1	0	0	0	0	0	2
Hazmat Incidents	0	0	0	1	0	0	0	1	0	2
Dam Failures	0	0	0	0	0	0	0	0	0	0
Freeway Hazard	2	2	1	2	0	0	0	0	0	8
Other	3	3	1	11	1	0	0	2	1	22
TOTAL	16	20	4	70	6	2	2	15	5	140



Concentrations of Closures and General Planning Implications

As can be seen from examining the above map, most of the closures are expected to occur within the Napa Valley. Transportation disruptions are expected along State Route 29 within and around the communities of Napa, Yountville, St. Helena and Calistoga.

While this area presents large census tracts due to its rural nature, the roads connecting the small communities are few. In most cases, these roads are not redundant and access to some of the rural communities along them might be severely impaired.

Specific Planning Considerations

West Napa Earthquake

Roads

- State Highway 29 is the only major north-south route for access to Napa County from outside areas. Multiple closures are expected along this route. These closures are of particular concern due to the lack of alternative arterials.
- State Routes 12 and 121 are also expected to be affected by multiple road closures either directly, or indirectly to the streets that feed these transportation corridors.

Bridges

- The Carquinez and Benicia-Martinez Bridges are the most direct links between the heavily impacted areas in the North Bay and the remainder of the region, particularly the East Bay. For planning purposes, it should be assumed that these bridges may be closed, at least for a few days. Emergency planners should expect that approaches to these bridges, as well as local roads feeding the bridges, will be affected by multiple road closures on at least one of their ends.
- Isolated road closures are possible, but less likely, which would affect the approaches to the other toll bridges in the region.
- In addition, non-retrofitted local roadway bridges and smaller bridges over the Napa River on local roads should be considered a weak link along transportation routes.

Airports

- The Napa County Airport is expected to be affected by multiple road closures servicing its facilities after this scenario earthquake.
- Access to the facilities at Sonoma Sky Park and the Sonoma Valley Airport is also expected to be affected by road closures, but not the extent of the Napa County Airport.
- Travis AFB may become the closest major airfield capable of handling large commercial and cargo jets. Therefore, this airport should plan for increased air and vehicle traffic, both immediately and long term, following this scenario earthquake.

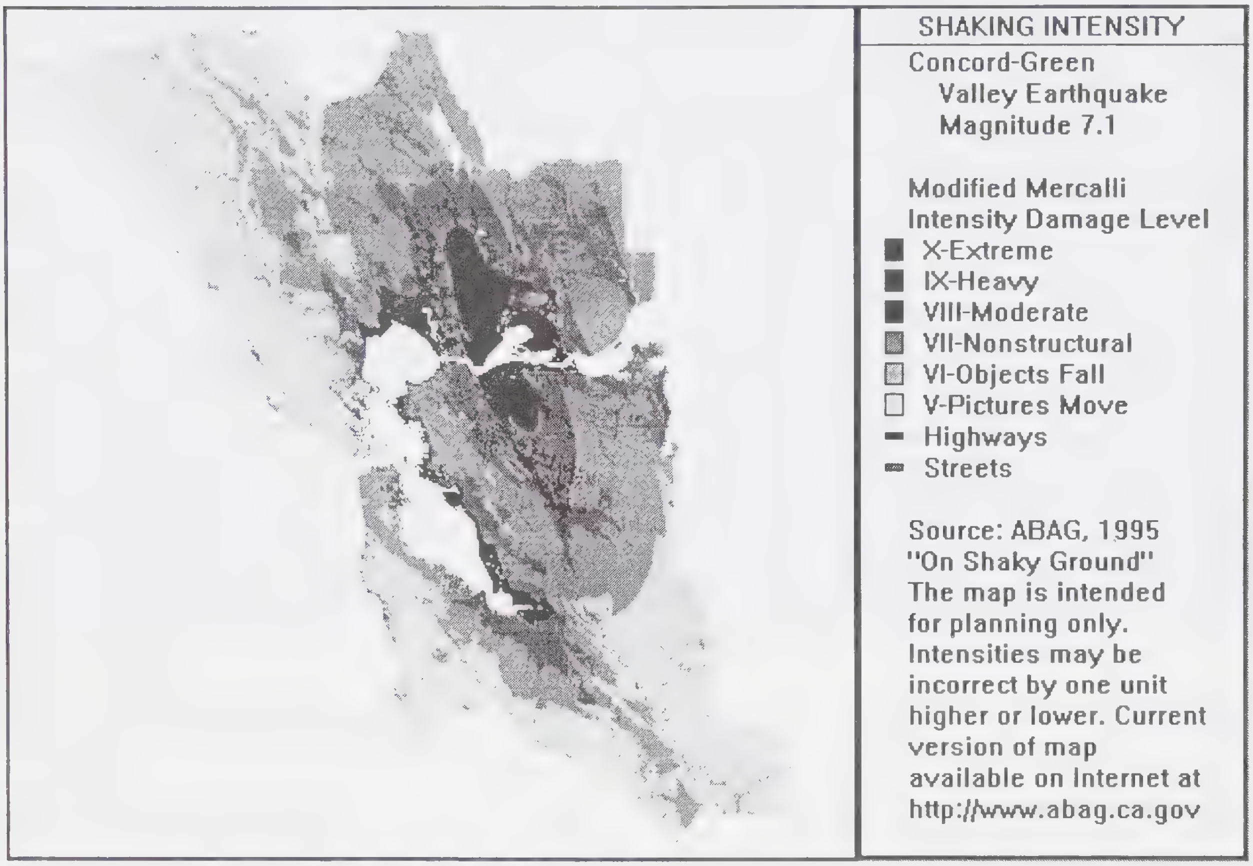
Ports

- It is unlikely that any port facilities will be affected by significant road closures as a result of this scenario earthquake. However, there may be some disruption at the Richmond and Benicia facilities.

Concord-Green Valley Earthquake Impacts

The Scenario

This scenario earthquake is for a magnitude 7.1 earthquake on the Concord-Green Valley fault in Contra Costa and Solano counties.



Distribution of Closures

An earthquake along the Concord-Green Valley fault would cause approximately ***337 road closures*** and would rank sixth in the scenarios modeled in this report. Although not as many closure are expected as in some of the other scenarios, this number is still 2.4 times as many as in either the Northridge or Loma Prieta earthquake. Almost half of the expected closures (49%) are expected to occur within Contra Costa County alone. Other than an earthquake along the Hayward fault, this earthquake is expected to generate the greatest number of closures within Contra Costa County.

The direct hazards of fault rupture, shaking and landsliding account for almost two thirds (62%) of the closures within Contra Costa County.

TRANSPORTATION SYSTEM CLOSURES DUE TO AN EARTHQUAKE ON THE CONCORD-GREEN VALLEY FAULT

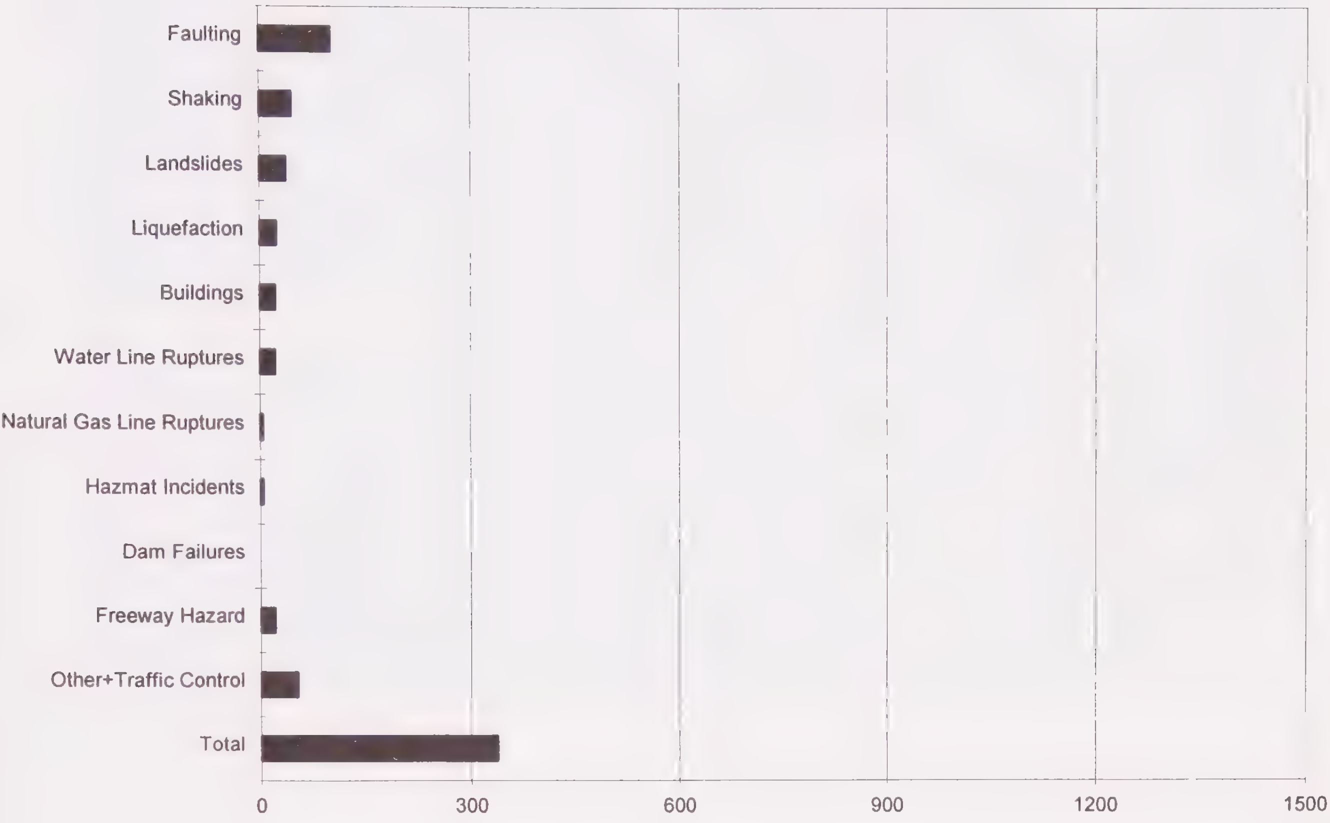
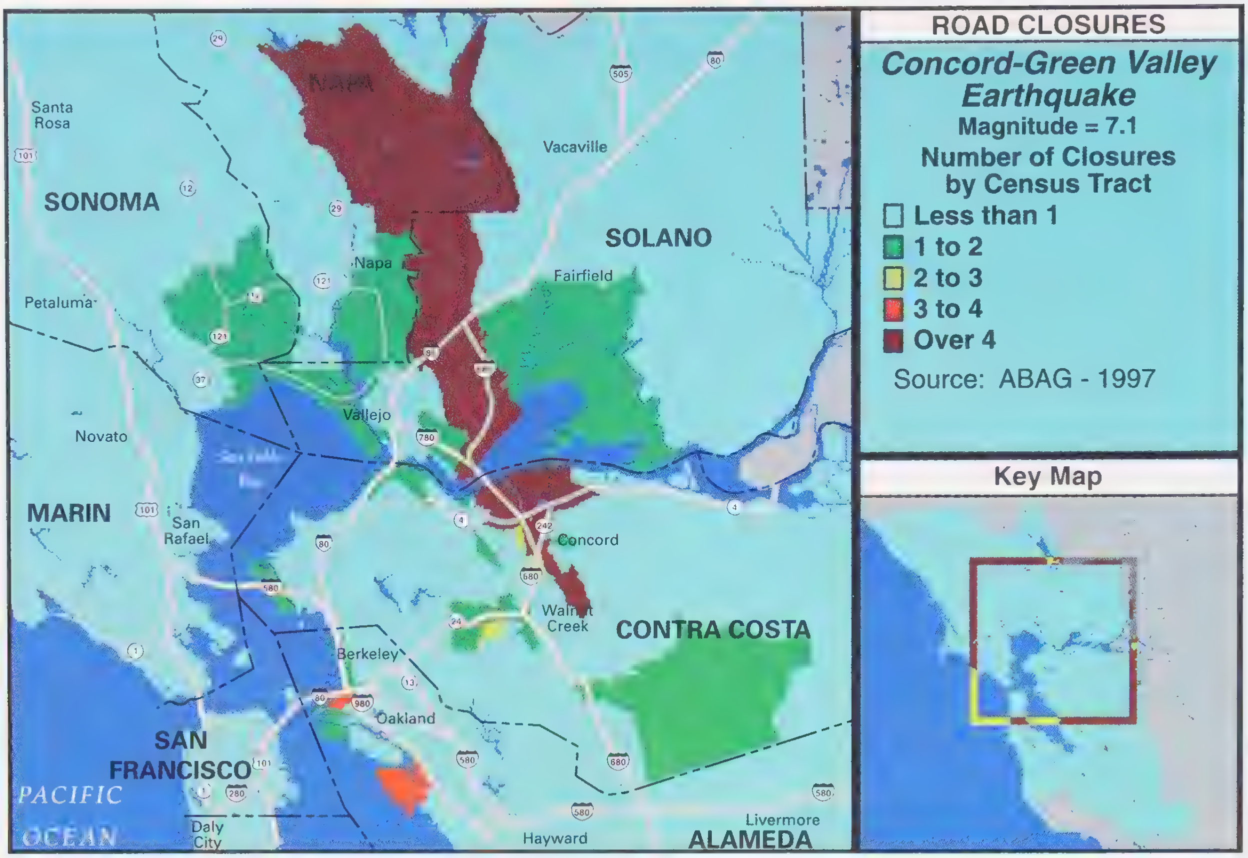


TABLE 40: Transportation System Closures by Hazard Type and County

Hazard Type	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	TOTAL
Faulting	0	61	0	2	0	0	0	39	0	102
Shaking	12	24	2	1	1	1	3	2	0	46
Landsliding	5	17	1	4	1	1	1	6	2	38
Liquefaction	12	4	0	0	0	0	0	5	1	24
Buildings	6	6	0	1	7	0	0	3	0	23
Water Line Ruptures	2	11	0	2	0	0	1	5	0	22
Natural Gas Line Ruptures	0	2	0	0	0	0	0	1	0	4
Hazmat Incidents	0	3	0	0	0	0	0	1	0	5
Dam Failures	0	0	0	0	0	0	0	0	0	0
Freeway Hazard	5	11	1	0	0	0	2	1	0	21
Other	8	26	1	2	2	1	2	12	1	53
TOTAL	52	164	4	13	11	4	10	74	4	337



Concentrations of Closures and General Planning Implications

As can be seen from examining the above map, there is a significant concentration of closures along segments of the I-680 corridor in Solano and Contra Costa counties. Areas within and around the cities of Benicia, Vallejo (Cordelia) and Martinez are expected to have significant disruptions within them and between them.

At the same time, while significant disruptions are expected on both sides of the Carquinez Strait, any potential effect on the connecting Benicia-Martinez toll bridge is particularly critical since this bridge is not redundant.

Finally, portions of eastern Solano and Contra Costa counties may experience serious access problems.

Specific Planning Considerations

Concord-Green Valley Earthquake

Roads

- The I-680 corridor is the key north-south route in the impacted area. Multiple closures are expected along this corridor.
- BART may be unable to pick up extra service in the I-680 corridor due to extensive damage to the supports for its older elevated sections, and may even contribute to blocking of roadways and highways.
- Parts of the I-80 corridor, particularly that portion near the I- 680 interchange, are expected to experience multiple road closures. Although the length of the affected roadway is only several miles, I-80 is a major route to and from the Bay Area.
- Emergency response planners should also anticipate that State Routes 4, 121, and 242 transportation corridors (including both the highways themselves and the local streets along these routes) will be affected by multiple closures.

Bridges

- The Carquinez and Benicia-Martinez Bridges are the most direct links between the heavily impacted areas in the North and East Bay. For planning purposes, it should be assumed that these bridges may be closed, at least for a few days. Emergency planners should expect that approaches to these bridges, as well as local roads feeding the bridges, will be affected by multiple road closures on at least one of their ends.
- Liquefaction and other hazards may affect the approaches, as well as feeder roads, to the other toll bridges in the region.
- In addition, non-retrofitted local roadway bridges on local roads should be considered a weak link along transportation routes.

Airports

- Emergency response planners should assume that Oakland International Airport, Buchanan Field in Concord, and Napa County Airport will be affected by multiple closures of roads servicing their facilities after this scenario earthquake.
- Alternative air facilities at San Jose or San Francisco International Airports and Travis AFB are expected to be more accessible. Therefore, these airports should plan for increased air and vehicle traffic, both immediately and long term, should other airports have access difficulties.

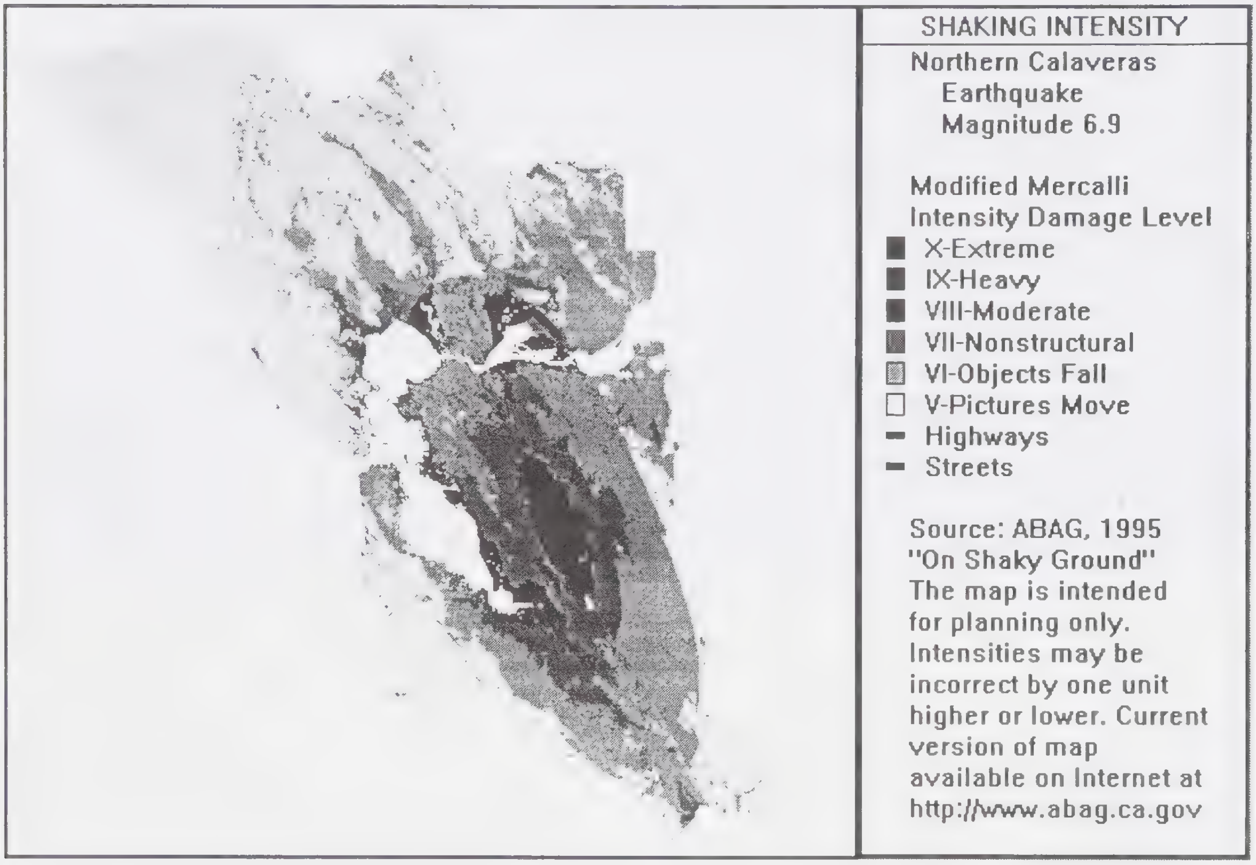
Ports

- The Port of Oakland is expected to be affected by several road closures after this earthquake. Oakland's facilities for large container ships are non-redundant in the immediate Bay Area. The Port of Kobe, Japan, experienced similar impacts following the Hyogo-Ken Nanbu earthquake in 1995. These facilities may be able to unload ships but not transport cargo out of the impacted area immediately following the earthquake.
- The Port of San Francisco, as well as other ports in southern California and along the entire west coast may experience increased shipping traffic should the Port of Oakland be heavily impacted by an earthquake.

Northern Calaveras Earthquake Impacts

The Scenario

This scenario earthquake is for a magnitude 7.1 earthquake on the northern segment of the Calaveras fault, extending from Danville in central Contra Costa County south to Calaveras Reservoir in northern Santa Clara County.



Distribution of Closures

An earthquake along the northern Calaveras fault would cause approximately ***291 road closures*** and ranks seventh out the eleven scenarios modeled in this report. Over half of the closures (54%) are expected to occur within Alameda County alone. The impacts are still significant. The total number of closures in Alameda County alone exceeds that experienced regionwide in either the Loma Prieta or Northridge earthquakes. Contra Costa County is expected to be the next most severely affected area, with over one fourth (28%) of the total closures.

The direct hazards of fault rupture, shaking and landsliding are expected to be a significant source of closures; they are expected to account for almost two thirds (65%) of the total closures in Alameda County.

TRANSPORTATION SYSTEM CLOSURES DUE TO AN EARTHQUAKE ON THE NORTHERN CALAVERAS FAULT

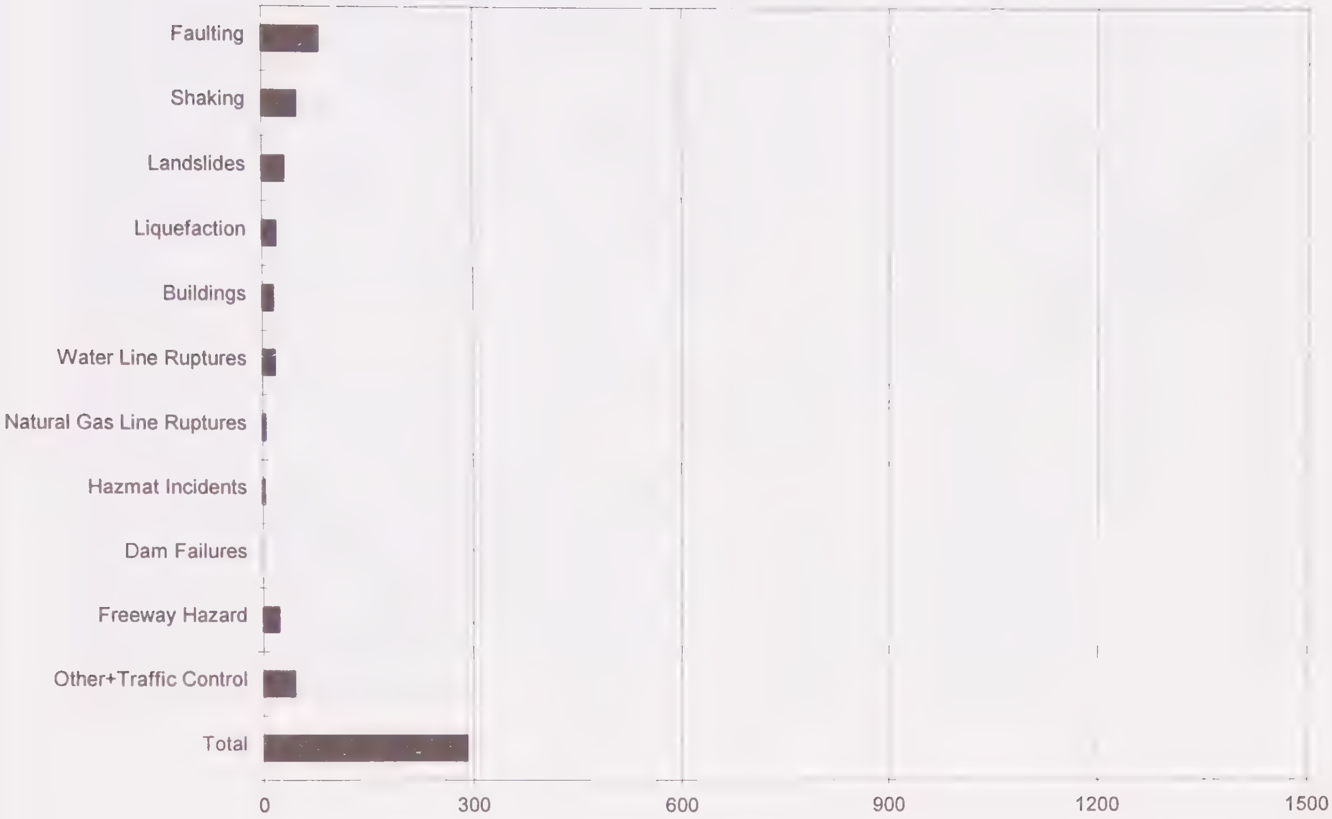
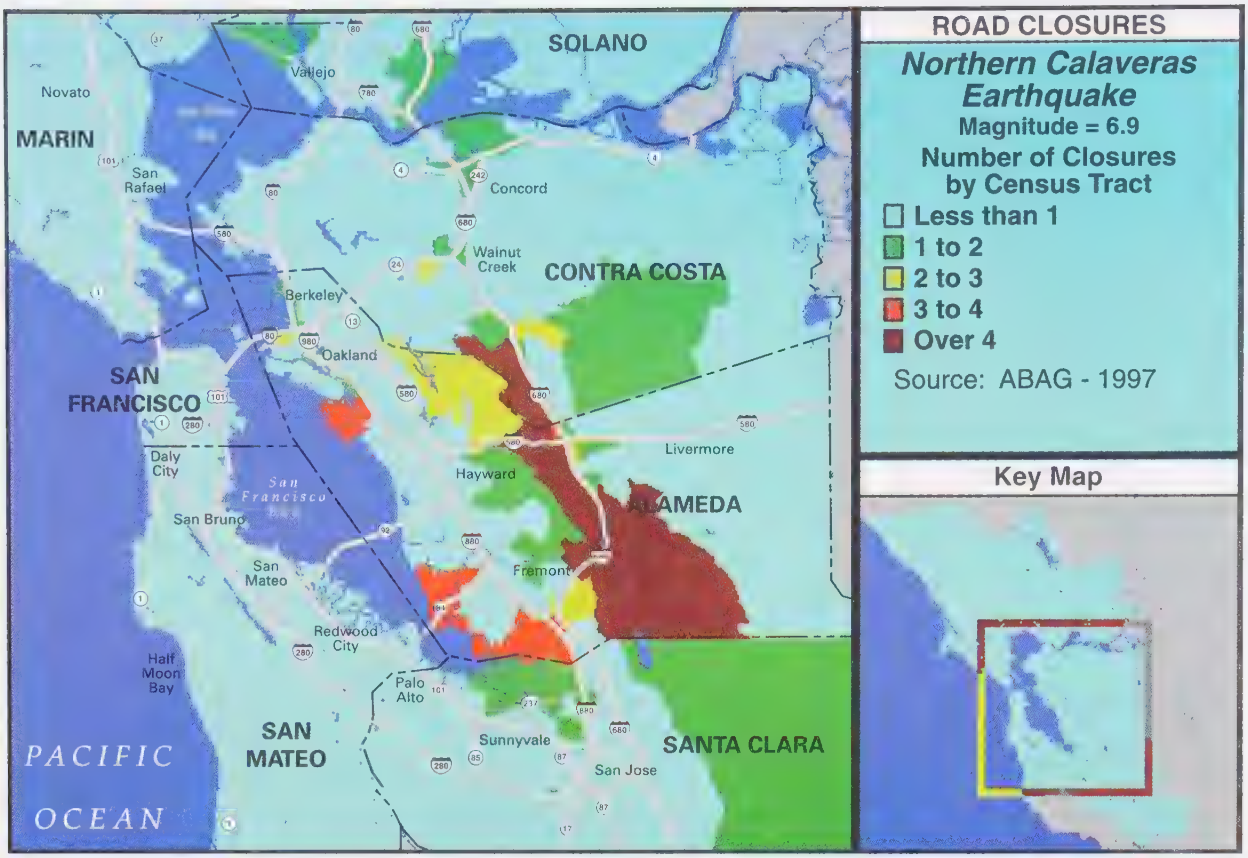


TABLE 41: Transportation System Closures by Hazard Type and County

Hazard Type	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	TOTAL
Faulting	53	28	0	0	0	0	0	0	0	81
Shaking	25	11	2	0	1	1	9	0	0	49
Landsliding	12	12	0	0	1	0	5	1	0	32
Liquefaction	12	3	0	0	0	0	1	4	0	20
Buildings	7	2	0	0	6	0	1	0	0	16
Water Line Ruptures	8	6	0	0	0	0	3	1	0	18
Natural Gas Line Ruptures	2	1	0	0	0	0	1	0	0	4
Hazmat Incidents	2	1	0	0	0	0	0	0	0	3
Dam Failures	0	0	0	0	0	0	0	0	0	0
Freeway Hazard	12	5	1	0	0	1	4	0	0	23
Other	24	13	1	0	1	0	4	1	0	45
TOTAL	156	82	4	1	9	3	28	8	1	291



Concentrations of Closures and General Planning Implications

As can be seen from examining the above map, most of the closures are expected to occur along portions of eastern Alameda and Contra Costa counties. Transportation disruptions are expected along portions of the I-680 and I-580 corridors, as well as along rural sections of State Route 84. Areas within and around the communities of Danville, Dublin and Pleasanton, are expected to experience the largest concentrations of closures.

- The Metcalf substation east of San Jose experienced violent shaking which caused all three of the live-tank circuit breakers to fail. Oil leaks appeared in five of nine current transformers connected to the circuit breakers, the majority at flanges. Some equipment anchors and support columns failed and shifted, but equipment was not lost. Many circuit breakers and bus connections that had been replaced after the Morgan Hill earthquake (1984) worked very well, and damage was less in 1989 than the 1984 event.
- The San Mateo substation along the central-western shore of San Francisco Bay experienced enough shaking to cause failure at three places on circuit breakers–a porcelain support column, the high-pressure air plumbing, and gaskets connecting two interrupter heads. Switch connections on a bus support structure also were damaged, and two cables disconnected. Two voltage transformers failed as well, and one bank of them exhibited oil leaks.
- The Monte Vista substation near Cupertino experienced violent shaking resulting in problems similar to the other substations. Failures occurred on a porcelain member of a voltage transformer, on post-insulator supports with some transfer buses falling down, and on expansion anchor bolts of a bus-support pad. A single-phase transformer sustained internal damage from the shaking.
- At the Newark substation, circuit breaker gaskets leaked.

Damage to PG&E's distribution system included downed lines, blown fuses, fallen and toppled poles, and some fallen pole-mounted transformers. In areas where underground transformers are located, the transformers themselves were not damaged, although some vaults in which they are bolted migrated in the softer geologic materials such as those found in the Marina District. Broken underground conduits were also observed in several places. However, these types of damage to the distribution systems are considered minor and are similar to what might be found after a strong winter storm. ***Thus, transportation access to the electrical distribution system is not nearly as critical as access to key power plants and substations, as well as to key service and office centers.***

Natural Gas

Within the PG&E service region, only three leaks occurred in the gas transmission and larger distribution mains from the Loma Prieta earthquake. Several miles of smaller distribution lines, as well as several thousand service meters, were replaced – primarily in the Marina District, Los Gatos, and Watsonville. All relighting of operating gas pilot lights and equipment (entailing 150,000 service calls) was completed throughout the region within a week with the assistance of crews from other utilities in the western portion of the U.S. ***Therefore, access to these thousands of leaks and tens of thousands of customers is critical. As with water supply agencies, PG&E service crews will need access to much of the street network.***

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Earthquake Engineering Research Institute, May 1990. "Loma Prieta Earthquake Reconnaissance Report" in ***Earthquake Spectra***: EERI Supplement to v. 6, Oakland, California, 448 pp.

Topposada, T.R., Borchardt, G., Hallstrom, C.L., Youngs, L.G., Gallagher, R.P., and Lagorio, H.J., 1994. ***Planning Scenario for a Major Earthquake on the Rodgers Creek Fault in the Northern San Francisco Bay Area***, California Division of Mines and Geology (CDMG) Special Publication 112, Sacramento, California, 249 pp.

Written and oral communications with Woody Savage, Geosciences Department, and Ed Matsuda, Senior Seismic Engineer, Pacific Gas and Electric, November 20, 1995.

Telecommunications

Introduction

Several companies provide customers with access to networks providing long-distance phone service. Primarily, however, this list of companies is dominated by AT&T, MCI and U.S. Sprint. All of these organizations updated and improved their systems dramatically during the 1980s as the telecommunications industry moved into the digital age.

The primary local provider of telephone, fax, and pager services in the Bay Area is Pacific Bell. Cellular phone companies, such as GTE MobileNet and CellularOne do offer mobile phone service, but ***nearly all cellular calls have at least one connection through the Pacific Bell network***. In the future, this somewhat monopolistic situation may change as the local telecommunications market enters the era of competition. In a small number of communities, service is provided by General Telephone; however, the majority of the region's communication needs is supplied by Pacific Bell.

Media industries (television, radio, and newspapers) are both part of, and rely on, the region's telecommunications system. ***All three media depend on power, communication, and transportation.*** During a natural disaster such as an earthquake, the public relies upon radio and television in particular for information which may affect it directly, and thus companies within these media need to have emergency planning procedures in place to remain operating during and after such events.

Phone Service

Pacific Bell has revamped its system organization, now using as a "hub-centered" approach rather than its old "linear-branch" system. Fully digital, the network contains a small number of Management Centers, and over 600 "End Offices" which provide points for customers to initialize a call. Connectors send calls through hubs which are operating centers that route the signals using digital switches. The operation of PacBell's local phone service is critical to all forms of telephone communication. ***Therefore, PacBell is most concerned about access to 51 of these End Offices.*** However, the network is designed with built-in redundancies, as many of the hubs are non-critical; that is, signals can be re-routed if operations are interrupted. Signals are sent via two simultaneous but different paths.

Switches in the End Offices can only serve a portion of the lines at any given time, as only a fraction of the lines are busy during any particular moment. With a sudden and dramatic increase in usage, a caller may have a wait for some time for a dial tone in order to place a call. The exception to this delay is the priority place on ***essential service lines*** – typically hospitals, police, fire, and other emergency response agencies. These calls will take up some portion of the capacity of the switches, and non-priority calls will be placed in a queue for connection when possible.

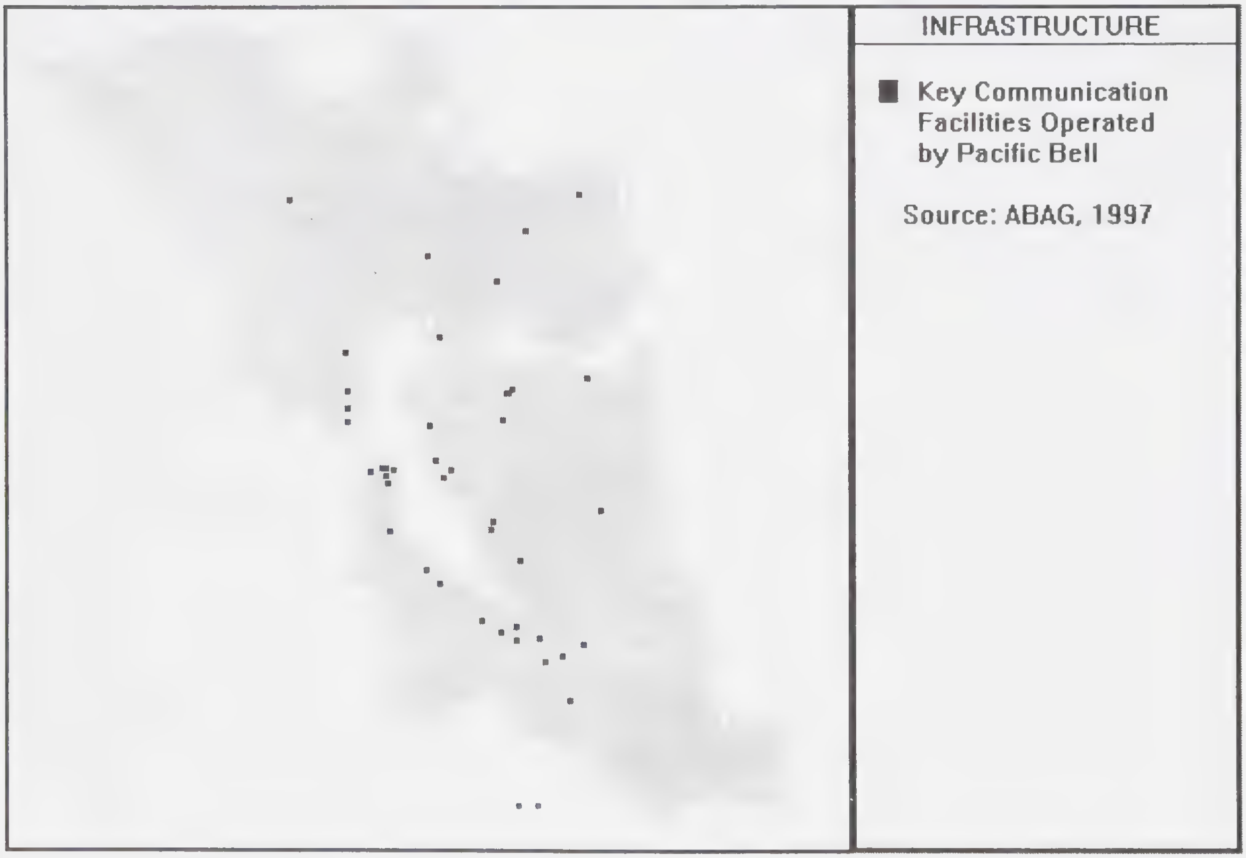
Long-distance carriers also have designed their networks which utilize digital technology, and have the capability to re-route calls using redundancies in their systems. Customer access to long-distance services from specific area codes can be limited via network load balancing.

Radio Communication

Voice radio systems are centered around a fixed, high-powered transmitter and a fixed antenna. Repeater stations are often employed to increase the range and quality of signals. Emergency response agencies (including police, fire, and 9-1-1 systems), plus cab companies and ham radio operators, use ultra-high frequency systems.

Location of Critical Communication Facilities

This map depicts 49 mapped critical PacBell "office" facilities in the Bay Area.



Bay Area Critical Communication Facilities

Experience in the Loma Prieta Earthquake

Telephone Systems

For long-distance carriers, a substantial increase in telephone traffic occurred just after the Loma Prieta earthquake took place. A little over one-third of the calls made to the area codes affected

by the earthquake within a day of the event were completed, but this total was nearly three times the normal daily volume of calls. Many of these calls were blocked by long-distance carriers and Pacific Bell to keep the systems from overloading. The number of calls which did go through were significantly higher than in previous high-volume events due to recent technological innovations (oral communication, Sambito and Grago, 1995). Some equipment used in AT&T's Oakland facility (most notably cable trays), exhibited minor problems, but with no loss of function. No damage to other equipment was reported.

Local carrier operations were affected much less by damage than by post-earthquake usage. Little damage occurred to the communication equipment of Pacific Bell. Service problems were primarily minor, caused primarily by loss of commercial power. While all central offices have backup batteries and generators, five generators at four offices were either unavailable for use or did not operate properly. One generator did not start, and four generators had mechanical problems.

Two circuit packs came out of their sockets in San Jose, causing a slight drop in service capacity. The main office in Oakland sustained structural damage, and although no communications equipment was directly affected, major disruption to service throughout northern California could have occurred had the building been lost. No lines in the system, either above or below ground, were reported damaged.

In the day following the earthquake, the volume of calls exceeded the average by 45%, causing delays in placing or completing calls, particularly between calls made between different central offices. For several days, service was spotty during peak-load times. Line load control, which allows the essential service lines to be prioritized, was not activated, and these lines (including 9-1-1 calls) experienced delays that were not expected.

Systems used within companies to route calls within the organization and connect to outside lines are called private branch exchanges (PBXs). Many of these networks had problems, most often due to commercial power loss and no backup system. When connections could not be made, many users blamed the commercial phone network for the difficulties rather than the exchanges. Seismic damage affected a few smaller PBXs.

Cellular phone systems use an array of radio transmitters and receivers which are connected through phone lines and microwave links to a switch (or to switches) at the cellular phone company. The switch completes calls made by connected customers, and at a faster rate than those for regular telephones. After the Loma Prieta earthquake, reports about the service on cellular phone systems were conflicting, with some describing better than regular phone service and others complaining about system overload. If a cell serving a particular area becomes saturated, service to all users in that cell is degraded. Since little damage occurred to these systems, the reports may be an indicator of various differences in demand among regional locations and thus cellular arrays.

Radio Communications

Many of the transmitter stations used to establish radio communications lost commercial power from the Loma Prieta earthquake. Repeaters were particularly vulnerable to power loss. Equipment operated by Pacific Bell performed much better, as they had been maintained and emergency power had been in place.

References

Earthquake Engineering Research Institute, May 1990. "Loma Prieta Earthquake Reconnaissance Report" in ***Earthquake Spectra***: EERI Supplement to v. 6, Oakland, California, 448 pp.

Topposada, T.R., Borchardt, G., Hallstrom, C.L., Youngs, L.G., Gallagher, R.P., and Lagorio, H.J., 1994. ***Planning Scenario for a Major Earthquake on the Rodgers Creek Fault in the Northern San Francisco Bay Area***, California Division of Mines and Geology (CDMG) Special Publication 112, Sacramento, California, 249 pp.

Written and oral communications with Bill Sambito and Scott Grago, Emergency Preparedness and Disaster Recovery Planning, Pacific Bell, October 25, 1995 and spring 1996.

WHERE ARE KEY FACILITIES CONCENTRATED AND WHAT ARE THE PLANNING IMPLICATIONS ?

Knowledge of the locations of key facilities involved in post-earthquake response and recovery is critical. These buildings or facilities will likely be the destinations for various responders, repair personnel, and earthquake victims following an earthquake, thus placing abnormal demands on the adjacent transportation network. These facilities can be viewed as providing the ***demand*** side of a supply-demand analysis for post-earthquake transportation facilities.

On the other hand, getting ***existing high traffic corridors*** back into services is the most critical need in terms of ***long-term recovery*** of the regional economy.

Key Emergency Facility Concentrations

As shown by the maps on the following pages, most of these key facilities are concentrated along a limited number of key transportation corridor segments. If one defines these segments from major transportation node to transportation node (that is, interchanges or other junctions of major transportation routes) the routes with the greatest concentrations of facilities are:

- I-880 from State Route 24 / I-980 to east State Route 238 / I-580 (the south Oakland corridor segment);
- I-80 from State Route 24 / east I-580 to State Route 4 (the north Oakland/Berkeley/ Richmond corridor segment);
- I-80 over the San Francisco - Oakland Bay Bridge;
- State Route 101 from San Francisco to the Dumbarton Bridge (the Peninsula corridor segment);
- State Route 1 from Half Moon Bay north to San Francisco (the San Mateo County coast corridor);
- I-580 from I-680 east to State Route 84 in Livermore (the tri-valley corridor);
- I-680 from State Route 24 in Walnut Creek north to the Benicia-Martinez bridge (the northern I-680 corridor);
- I-580 from I-80 in Richmond to State Route 101 in San Rafael (including the Richmond-San Rafael Bridge); and
- State Route 101 from San Francisco to State Route 37 in Novato (the Marin - 101 corridor segment).

Thus, from a planning perspective, these nine corridors have the greatest priority for pre-earthquake planning, particularly during the first few days following a major earthquake.

Transportation Planning for Regional Economic Recovery

The corridor segments with the highest use, based on 2-hour peak volume, is similar, but not identical, to the segments defined by highest concentrations of key facilities. These corridor segments include:

- I-80 from State Route 24 to west I-580 (the north Oakland/Berkeley/Richmond corridor segment);
- I-80 over the San Francisco - Oakland Bay Bridge;
- State Route 101 from San Francisco to the San Mateo Bridge (the northern Peninsula corridor segment); and
- State Route 24 from Oakland to Lafayette.

Note that only three corridors appear on both lists:
- I-80 from State Route 24 to west I-580 (the north Oakland/Berkeley/Richmond corridor segment);
- I-80 over the San Francisco - Oakland Bay Bridge; and
- State Route 101 from San Francisco to the San Mateo Bridge (the northern Peninsula corridor segment).

Method of Analysis

Key Emergency Facilities

Data on the location of key facilities was collected from each category of emergency transportation user.

In an effort to assign equal importance to each category of facility, each was assigned an equal number of importance "points," (in this case, 1000 points). Thus, since there are only 51 PacBell key communications facilities, each would be assigned approximately 20 points. In another example, if there are 93 community, trauma and military hospitals, each is assigned 11 points. This scheme weighs the 503 fire stations as 2 points each, making these types of facilities less controlling of the overall map. In addition, because there are over 2000 water facilities, making the weight of each as only 0.5 point, the decision was made to only include the 52 water supply treatment facilities in this analysis, weighing their importance at 19 points each. This decision does not mean that other types of water facilities are not important, but that they do not tend to be concentrated in a few locations.

The number and weight for each facility type is summarized in Table 31. Note that facilities not essential in an emergency are not included in this assessment.

This process needs one additional type of weighting, however, because facilities tend to be concentrated in urban areas within census tracts that are small. Thus, the concentration maps which follow are corrected to show ***density of facilities per land area*** (acres) of census tract.

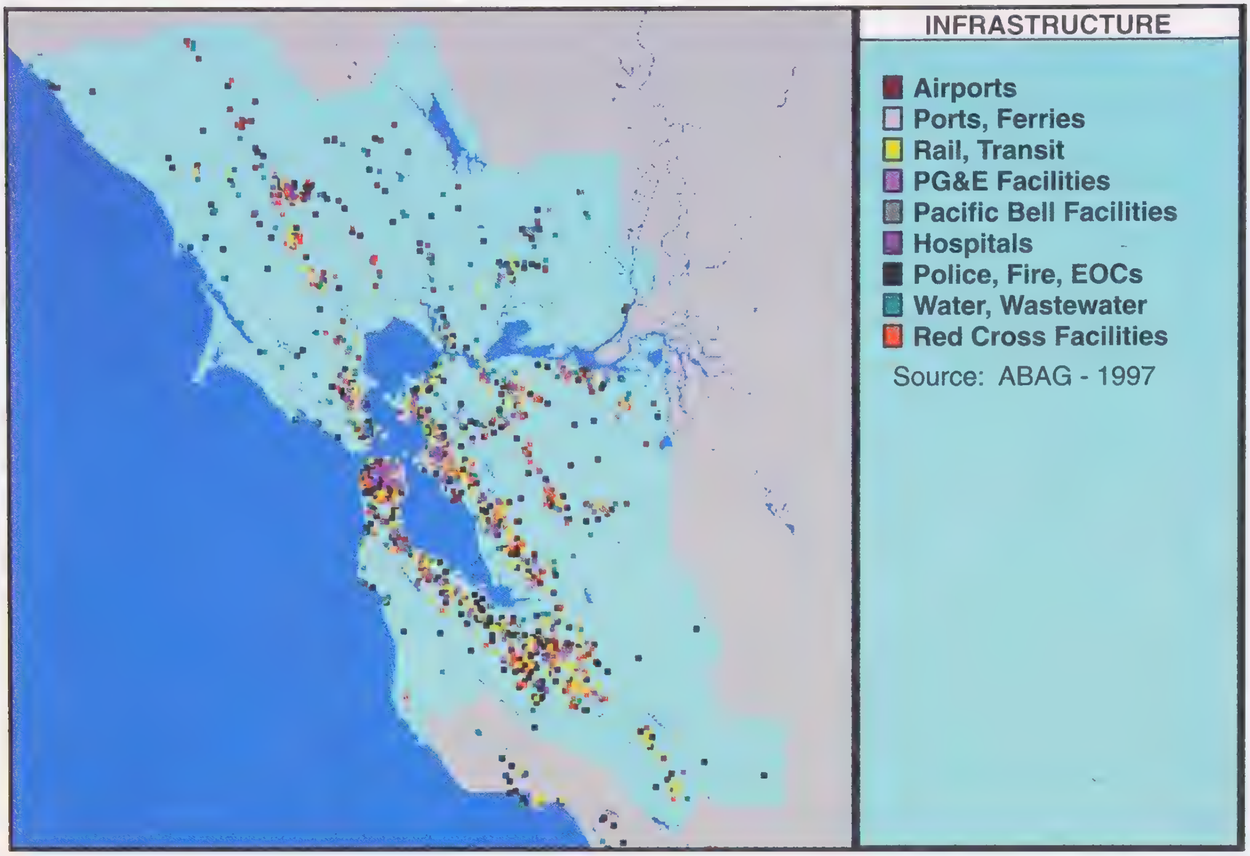
High Use Segments

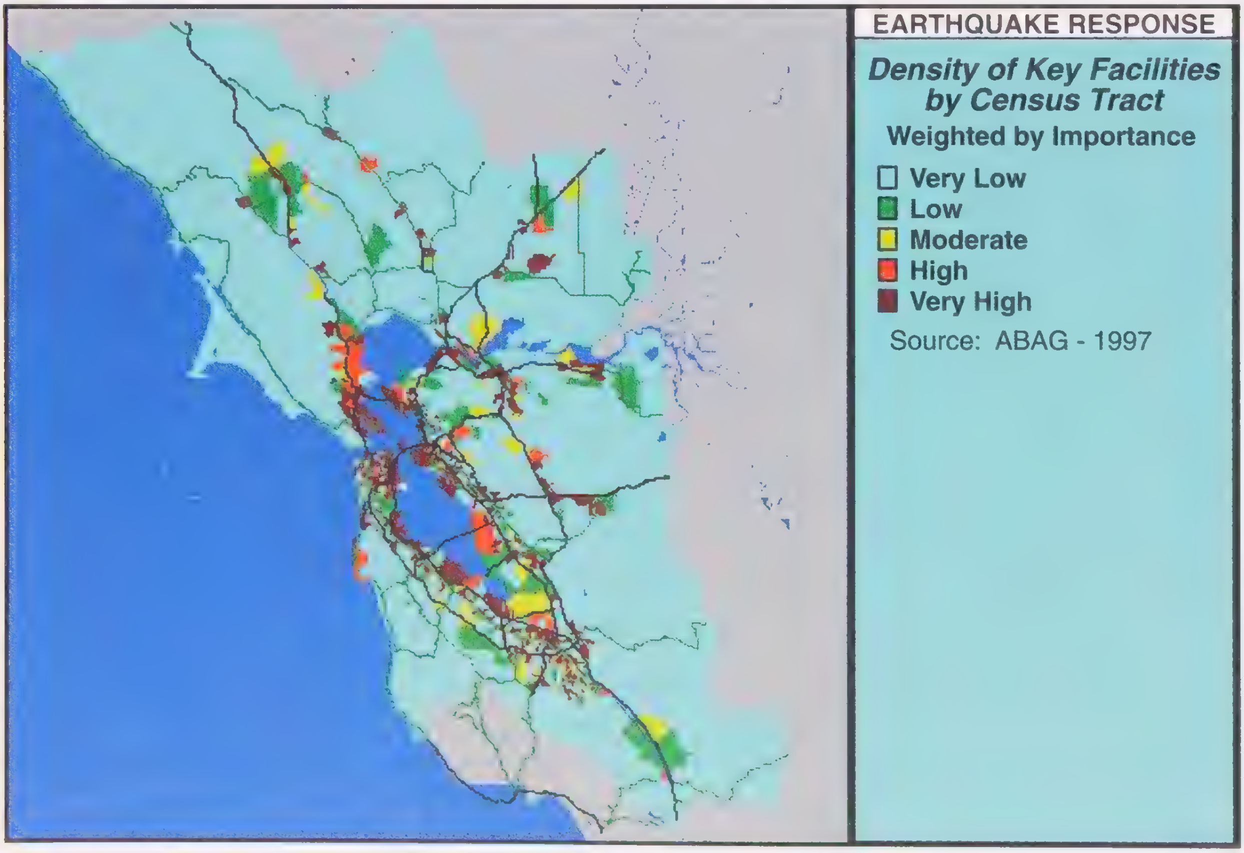
The transportation links with the highest peak volumes were provided by the Metropolitan Transportation Commission (personal written communication, Jeff Georgevich, April 1997).

TABLE 31: Relative Importance Coding of Facilities Used in Determining Concentrations of Key Facilities Using Transportation for Post-Earthquake Response and Recovery

[Summarized by land use classification categories. Facilities in Santa Cruz County are excluded.]

Category	Description	Current "Importance"	Number of Facilities
1241	Hospital - Designated Trauma Center	**11**	8
1242	Hospital - Community Hospital	**11**	84
1254	Military Hospital	**11**	1
1263	Fire Stations	**2**	487
1264	Police Stations and Sheriffs Offices	**2**	103
1266	County Emergency Operations Centers - EOCs	**2**	9
1291	Red Cross Shelters	**5**	174
1292	Red Cross Food Suppliers (in Bay Area)	**5**	12 (9 with data)
1293	Red Cross Supply Trailers	**5**	38 (no addresses)
1294	Red Cross Alternate Headquarters	**5**	8
1295	Red Cross Zone / Chapter Locations	**5**	13
1413	Transit - Park and Ride Lots	**6**	146
1414	Transit - Truck and Bus Maintenance Yards	**6**	35
1421	Rail Passenger Stations (BART/Amtrak/CalTrain)	**12**	80
1431	Commercial Airport Passenger Terminal	**19**	3
1432	Commercial Airport Air Cargo Facility	**19**	2
1433	Commercial Airport Airline Maintenance	**19**	2
1434	Commercial Airport Runway	**19**	3
1435	Commercial Airport Utilities	**19**	2
1436	Commercial Airport Other	**19**	3
1437	Public (General Aviation) Airfield	**19**	21
1438	Private Airfield	**19**	13
1256	Military Airport	**19**	2
1259	Closed Military Airports (with airfields intact)	**19**	3
1441	Commercial Port Passenger Terminal	**20**	1
1442	Commercial Port Container Terminal	**20**	11
1443	Commercial Port Oil and Liquid Bulk Terminal	**20**	6
1444	Commercial Port Other Terminal & Ship Repair	**20**	18
1445	Commercial Port Storage Facility or Warehouse	**20**	3
1447	Ferry Terminal	**20**	10
1451	Electricity - Power Plant	**16**	3
1452	Electricity - Key Substation	**16**	28
1454	Electricity - Service Center	**16**	14
1455	Electricity - Key Office or Building	**16**	14
1456	Natural Gas Facility	**16**	3
1461	Wastewater Treatment Plant	**14**	69
1471	Water Supply Treatment Plant	**19**	52
1484	Communications - PacBell "Offices"	**20**	49


INFRASTRUCTURE
Airports
Ports, Ferries
Rail, Transit
PG&E Facilities
Pacific Bell Facilities
Hospitals
Police, Fire, EOCs
Water, Wastewater
Red Cross Facilities
Source: ABAG - 1997


EARTHQUAKE RESPONSE
Density of Key Facilities by Census Tract
Weighted by Importance
Very Low
Low
Moderate
High
Very High
Source: ABAG - 1997

WHAT ARE THE CURRENT PREPAREDNESS ACTIVITIES OF TRANSPORTATION PROVIDERS ?

Overview

Prior to making recommendations on how transportation providers and others should better prepare for future earthquakes, it is essential to review the current emergency preparedness activities of the transportation providers related to response, particularly ***during the first 72 hours after an earthquake. Note that this is not a comprehensive review of the effectiveness of those capabilities, but rather an overview of the current status of those programs.***

Transportation Agency Coordination

The Metropolitan Transportation Commission (MTC) developed its ***Model Operator Contingency Plan*** (1993) and distributed the document to all transit and ferry operators. This plan provides guidance for emergency preparedness, response, and mitigation measures for equipment and facility damage – activities which may be undertaken by transportation providers. In addition, MTC and a task force of the Bay Area Partnership recently adopted the **Trans Response Plan** (TRP) concept (Feb 1997). The TRP concept creates a multimodal transportation response that is integrated into the overall emergency response for the nine-county area.

California Department of Transportation

Caltrans has established a set of emergency response policies which include:
- minimize the loss of life and property;
- protect State-operated facilities and the State highway system;
- maintain and provide up-to-date damage and operations information to public, media, local jurisdictions, the Governor, State legislators, as necessary;
- open damage State transportation system components as soon as possible;
- cooperate with other key agencies at the local, State and federal levels;
- support the State emergency-response efforts by the California Governor's Office of Emergency Services (OES), California Highway Patrol (CHP), and local jurisdictions; and
- conduct periodic drills and exercises in cooperation with other public agencies.

Caltrans' typical emergency response activities include:
- planning and implementing long-term traffic control and evacuation plans in cooperation with CHP;
- assessing damage to State highways, as well as disseminating timely and accurate information regarding the status of those highways and available detours;
- activating Caltrans Emergency Resource Centers (ERCs) and staffing other State and local emergency centers;
- establishing route recovery plans;
- emergency contracting for highway reconstruction;

- providing engineering and technical assistance to OES and other State and local government agencies relative to transportation services;
- establishing a liaison with the Federal Highway Administration regarding the status of the highway system;
- supporting local public works departments; and
- soliciting general aviation support.

Caltrans' emergency response priorities may generally be summarized as:
- traffic control;
- damage assessment; and
- route recovery.

In addition, Caltrans has emergency response resources, available in the event of an emergency, including:
- a 24-hour transportation management center with access to Bay Area broadcast and new agencies;
- a Communication and Dispatch Center;
- an Emergency Resource Center with emergency power, water, and supplies;
- transportation engineering, highway maintenance, and public information personnel to staff command post(s);
- traffic control devices such as barricades, cones, highway signs, and arrow boards;
- traffic management and highway maintenance equipment;
- mobile satellite and other communications systems; and
- on-call HAZMAT, freeway service patrol and emergency construction contractors.

California Highway Patrol (CHP)

The CHP has established a set of plans and priorities to implement in the event of an earthquake. First, an area command provides for assessing the condition of the CHP's own facilities and routes (which are areas assigned to individual officers). In areas with traffic problems, the CHP is responsible for short-term traffic control during the time before Caltrans employees arrive. The agency is also responsible for lifesaving efforts in these areas.

In addition, Emergency Resource Centers are in place at the eight divisions of the state. These Centers supply resources to incident commanders; the CHP is involved in non-criminal matters occurring on state highways and county roads. Resources may include officers, weapons, protective equipment, vehicles, and communications. Also, the CHP works with state OES, the Governor's Office, or the military to use planes if necessary for air support or far-reaching distribution of agency resources.

Air Transportation Facilities

Because of the size and importance of commercial airports, emergency operations are well planned at each facility. San Francisco has an Emergency Operations Center (EOC), its own in-

house 9-1-1 system, backup diesel generators, and a mobile communications command post. Oakland has an emergency response team, and all utilities are supplied on-site: power, water, gas, and sewage. San Jose also has backup utilities and emergency planning capabilities.

Marine Transportation Facilities

For the Port of Oakland, the emergency preparedness program includes divers and fire fighters for emergency operations, coordinated efforts with the Oakland Fire Dept., and mandated training. Contingency plans are in place for communications and power.

Because of damage during Loma Prieta, earthquake awareness at the Port of San Francisco has improved significantly. Recognition that the Port is a lifeline should bridges be knocked out of service is part of San Francisco's emergency response plan. Contingency plans are being developed for loss of transportation and power.

At Richmond, emergency operations control is through the city's fire department. The Port has no backup plans for loss of resources, perhaps because none of these resources are supplied on-site. (PG&E supplies the power, and the City of Richmond provides municipal water.) Both Richmond and Redwood City are effectively landlords within the maritime industry, so the movement of goods are more tenants' responsibilities than the ports'. Thus no facility-wide emergency plan is in place for either of these two ports. The major tenants manage their equipment and in theory have their own emergency plans. The scale of operations are small enough such that the ports have no backup plans for loss of resources.

The Port of Benicia has an emergency operations plan, but more importantly the Port itself is part of the contingency plans of all of the oil refineries in Contra Costa County. The pier, storage areas (for autos), and petroleum operations all meet seismic codes. There are also liquid storage tanks on site, but those are owned by the refineries. Contingency plans have been developed for transportation, power, telecommunications, and water.

Rail Transportation Facilities

Commuters and local travelers depend on adequate rail service, so emergency operations are well planned at each agency. BART has an EOC, as well as an earthquake alarm system throughout its station and track matrix. The alarms are designed to notify central operations when shaking intensities exceed 0.1g, and train operators are then told via radios to stop or slow down. Backup power is only available for station lighting, as the quantity of traction power to run the trains is significant. This minimal power contributed to emergency operation difficulties immediately after the Loma Prieta event. All trains are supplied with mobile radios for emergency communications. CalTrain also has an emergency operations plan, and backup communications. Amtrak is required to meet all federal safety regulations, but does not have as sophisticated an emergency preparedness program pertaining to seismic issues as do BART and CalTrain.

References

Metropolitan Transportation Commission, 1992. ***San Francisco Bay Regional Transportation Earthquake Response Capability Master Plan***: MTC, Oakland, California.

Metropolitan Transportation Commission, 1993: ***Model Operator Contingency Plan***, prepared by VSP Associates, Barbara Foster Associates and G&E Engineering Systems: MTC, Oakland, California, Section IV and Section VIII.

Metropolitan Transportation Commission, 1994. ***Regional Airport System Plan Update – San Francisco Bay Area***: MTC, Oakland, California.

Metropolitan Transportation Commission, 1997. ***Trans Response Plan (TRP)***: MTC, Oakland, California.

San Francisco International Airport, Feb. 15, 1991. ***Information Package – San Francisco International Airport***: San Francisco International Airport, San Francisco, California, 23 pp.

Written and oral communications occurred with the following:

- ***Caltrans*** - Sean Nozzari, Traffic Systems, Caltrans District 4, January 1997.
- ***CHP*** - Charles Kidder, Captain, Oakland, California Highway Patrol, December 2, 1996.
- ***Airports and Ports*** - Mark O'Brien, Manager, Environmental Health and Safety Compliance, and Jane Keegan, Risk Manager, Port of Oakland and Oakland International Airport, as well as Colleen Bell, Consultant, Safety and Loss Prevention (formerly with the Port of Oakland and as of 1997 with the City of Oakland Office of Emergency Services). October 12, 1995.
- ***Ports*** - Ben Kutnick, Director of Administration, Port of San Francisco, November 2, 1995.
- ***Ports*** - Joe Gaidsick, Vice President, Benicia Port Terminal Co., November 14, 1995
- ***BART and Rail*** - Kathryn Roth, Safety Specialist, and Mark Chiu, Manager, Civil/Structural Engineering, Bay Area Rapid Transit District (BART), February and November, 1996.
- ***Transit*** - Nancy Okasaki, Metropolitan Transportation Commission, Nov. 1996.

WHAT ARE WE PREDICTING WILL HAPPEN TO OUR TRANSPORTATION SYSTEM IN FUTURE EARTHQUAKES ?

The following pages summarize the results of the models for each scenario. The earthquake summaries provide

- estimates of road closures by cause (hazard) type and by county; and
- estimates of the location of these closures using subregional thematic maps showing the approximate number of road closure by census tract area.

ABAG recommends that this entire report be read before using the numbers for emergency or mitigation planning.

Note that this modeling process does not include:

- secondary disasters (such as huge fires, toxic gas releases far larger than Northridge or Loma Prieta, or dam collapse);
- possible road closures created to locate emergency housing; or
- extensive ground failures due to ground saturation associated with a very large winter storm.

The values are aggregated from modeling performed on individual census tracts. As with most types of statistics-based modeling, total values are more accurate than values for specific counties or hazards.

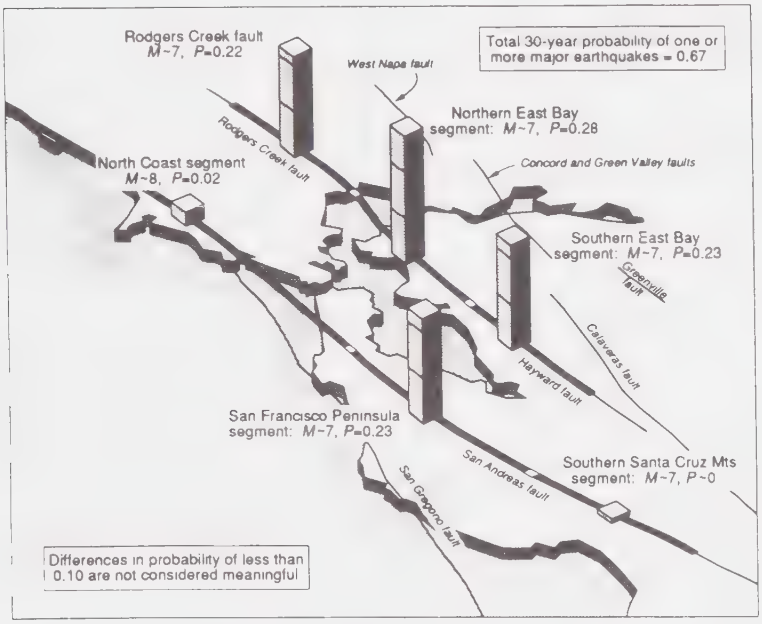
We examined the impact of 11 different scenario earthquakes.

The following pages detail estimates of road closures based on the occurrence of 11 different scenario earthquakes.

Fault segments generate ***"characteristic"*** earthquakes. Some faults tend to generate earthquakes with up to magnitudes 5 and 6. However, at least ten fault segments in the Bay Area can store up enough energy to generate earthquakes of magnitude 7 or so. These faults characteristically generate large earthquakes, not magnitude 5 and 6 events. The concept of "characteristic" earthquakes means that we can anticipate the actual damaging earthquakes that will occur on these fault segments. These anticipated events are the ***scenario earthquakes*** depicted in the color intensity maps that follow.

All of these earthquakes are likely events.

The source faults for these earthquakes, together with other major faults in the Bay Area, are shown on the map on the opposite page.



30-YEAR PROBABILITIES (*P*) OF LARGE EARTHQUAKES ($M \geq 7$) IN THE SAN FRANCISCO BAY REGION

Column heights are proportional to 30-year probability of earthquake rupture

Courtesy of the U.S. Geological Survey[1]

The probability of one of these scenario earthquakes occurring varies from fault segment to fault segment. The two Hayward fault segments, the Rodgers Creek fault, and the San Andreas Peninsula segment are felt to have, roughly, a probability of one in four of occurring in the next 30 years[31]. The recurrence of earthquakes on the other fault segments is less well understood; although equivalent probabilities are being developed, they are not available at this time. The likelihood that the entire Hayward fault will rupture at once is not known; experts have speculated that between one-in-four to one-in-two Hayward earthquakes will involve the entire fault, for a probability of 5-15% in 30 years.

However, information on long-term fault slip rates indicates that large earthquakes might be generated on all of these faults at least once in every 200 to 700 years. Since, in many cases, the date of the last large earthquake has not been determined, yet was at least 100 years ago, the possibility of large earthquakes on any of these fault segments is of great concern.

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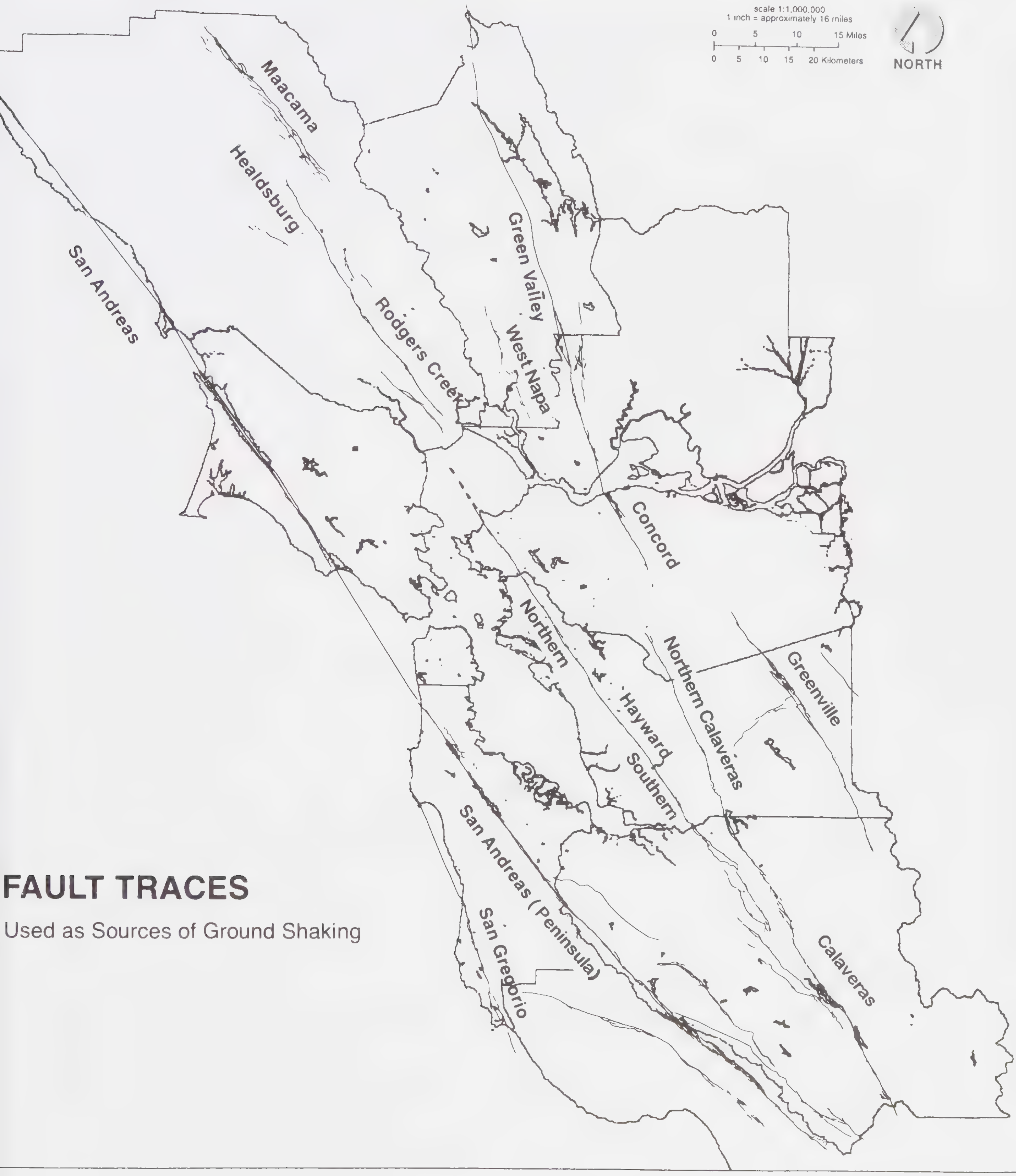
[31] Working Group on California Earthquake Probabilities (1990). ***Probabilities of Large Earthquakes in the San Francisco Bay Region, California***: U.S. Geological Survey Circular 1053, 51 pp.



FAULT TRACES

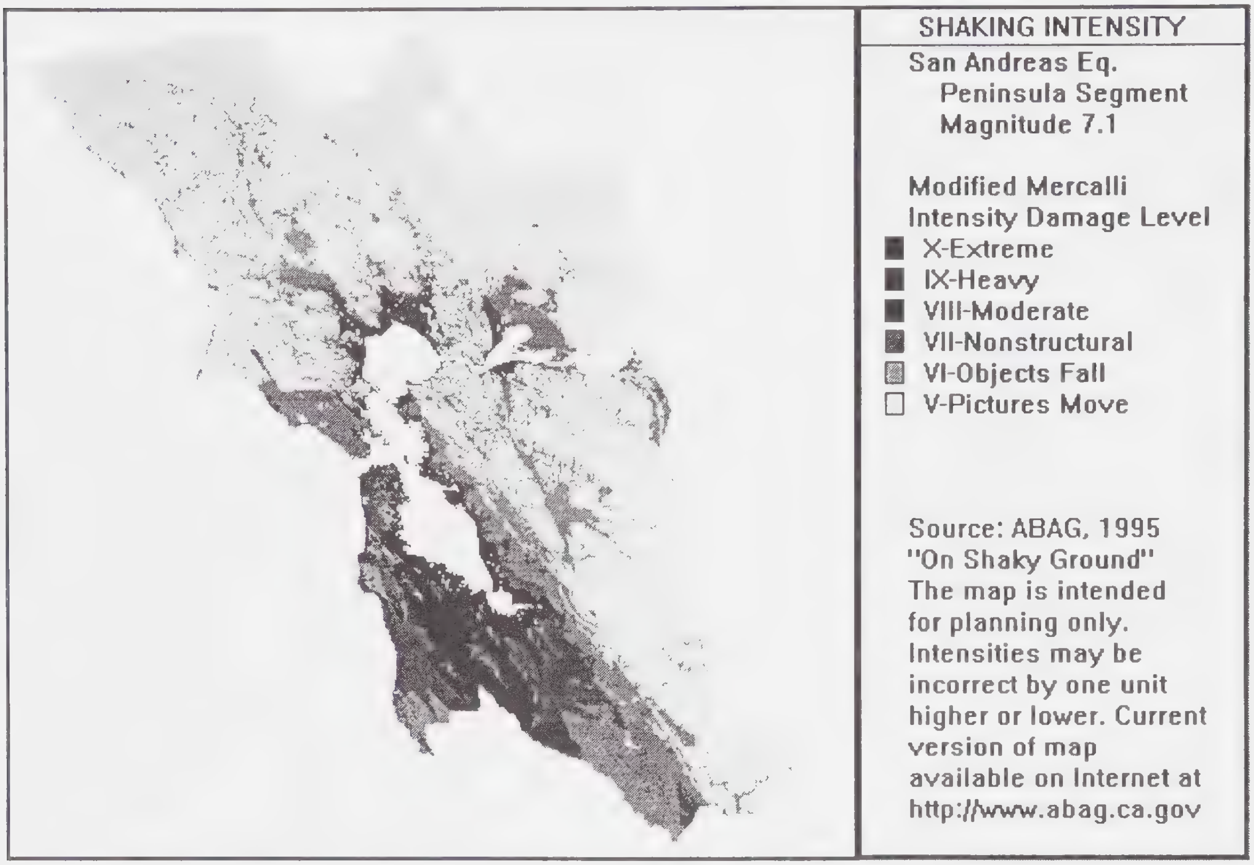
Used as Sources of Ground Shaking

Source: *On Shaky Ground* – 1995
ABAG©
Association of Bay Area Governments

San Andreas Earthquake -- Peninsula Segment -- Impacts

The Scenario

This scenario earthquake is for a magnitude 7.1 earthquake on the Peninsula segment of the San Andreas fault.



Distribution of Closures

An earthquake along the Peninsula segment of the San Andreas fault would cause approximately ***428 road closures***. Of these closures, most (39%) are predicted to be within San Mateo County. Most of the rest of the total forecasted closures are predicted to be in Santa Clara (26%), San Francisco (20%) and Alameda (10%) counties.

It is important to note the differences in the types closures that we are predicting. While in San Francisco two thirds of the closures are expected to be generated by building damage, in San Mateo and Santa Clara counties, half of the closures are expected to be due to fault rupture and shaking. The existing degree of urbanization within each area plays an important role in determining the type of closure within each county.

TRANSPORTATION SYSTEM CLOSURES DUE TO AN EARTHQUAKE ON THE PENINSULA SEGMENT OF THE SAN ANDREAS FAULT

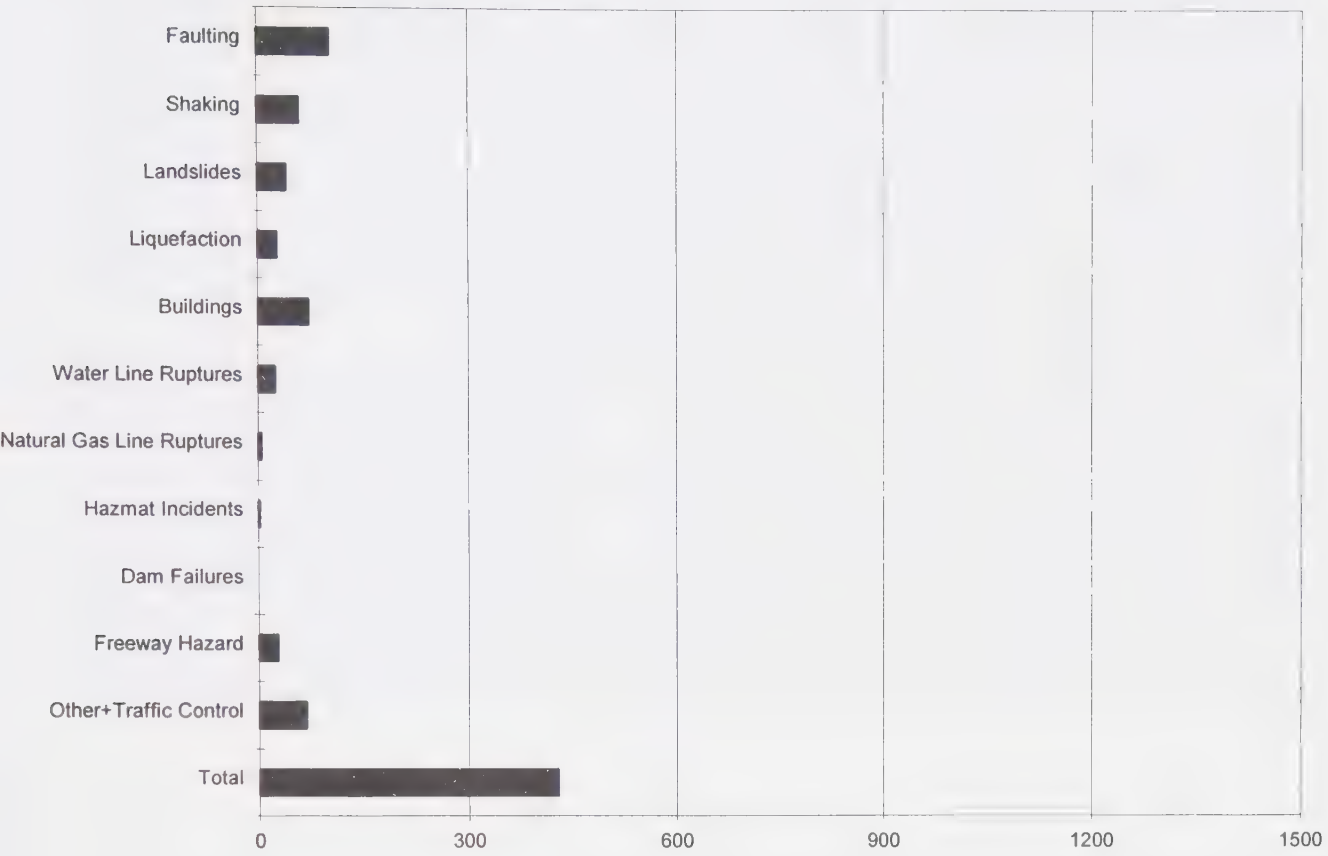
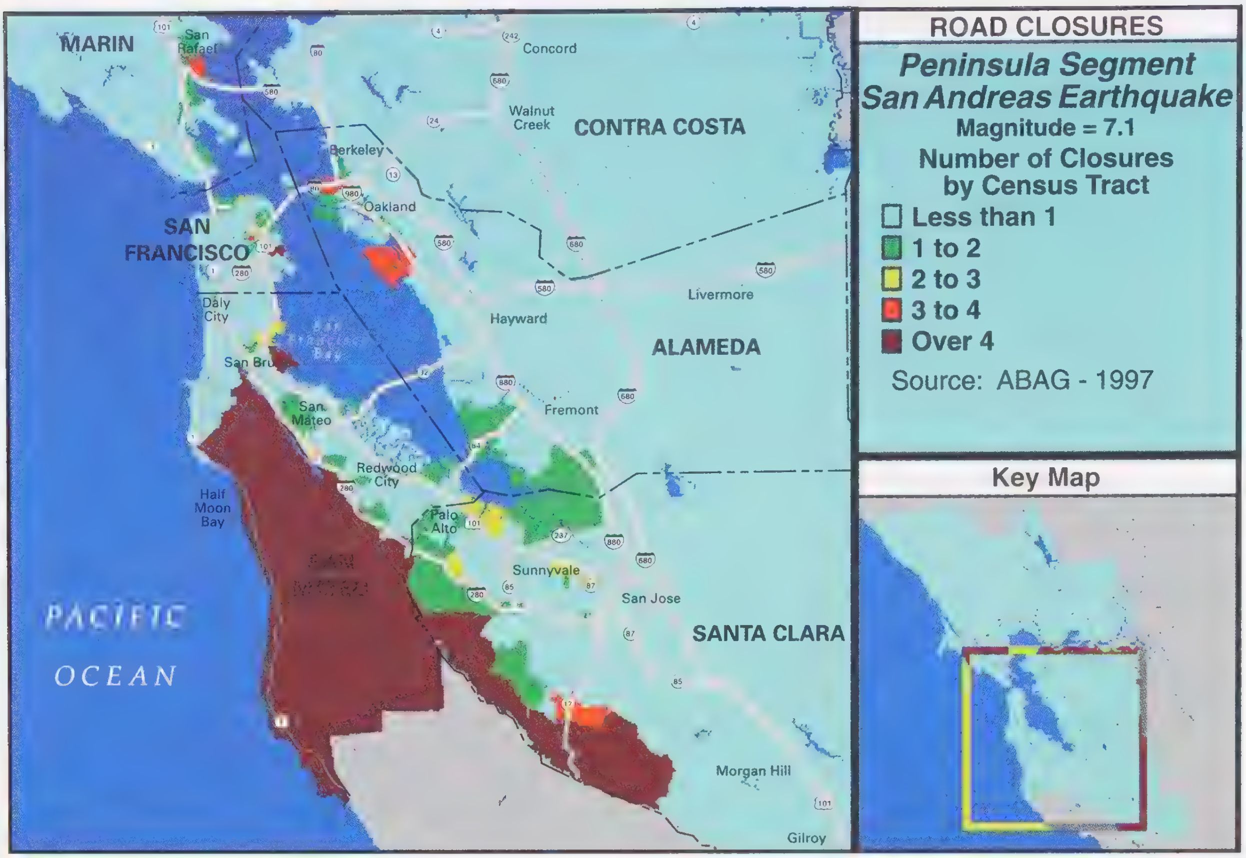


TABLE 32: Transportation System Closures by Hazard Type and County

Hazard Type	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	TOTAL
Faulting	0	0	0	0	0	68	35	0	0	103
Shaking	9	1	4	0	4	21	20	0	0	60
Landsliding	2	1	4	0	3	19	12	0	0	41
Liquefaction	12	0	6	0	7	2	1	0	0	28
Buildings	5	0	1	0	53	8	5	0	0	72
Water Line Ruptures	1	0	1	0	2	10	9	0	0	24
Natural Gas Line Ruptures	0	0	0	0	0	2	2	0	0	5
Hazmat Incidents	0	0	0	0	0	1	1	0	0	2
Dam Failures	0	0	0	0	0	0	0	0	0	0
Freeway Hazard	4	0	2	0	2	10	9	0	0	27
Other	6	1	3	0	13	26	17	0	0	67
TOTAL	41	4	21	0	84	166	111	0	1	428



Concentrations of Closures and General Planning Implications

As can be seen from examining the above map, most of the closures are expected to occur along the West side of the San Mateo peninsula. The rural areas around Half Moon Bay, San Gregorio and Pescadero are expected to experience severe damage. The major access routes for these rural areas are State Routes 1, 9, 35, 84 and 92. It is important to note that these roads are located in heavily impacted areas and are not redundant. Access to some of the rural communities along them is likely to be severely impaired.

Interstate Highway 280 runs parallel to the fault source for this earthquake, and also is likely to be affected.

Within San Francisco, most of the disruptions to the local transportation system are expected to occur in landfill areas adjacent to the Bay. The high urban density of these areas coupled with their soil type make them areas which are highly susceptible to earthquake damage and to disruptions to the local streets.

Specific Planning Considerations

San Andreas Earthquake - Peninsula Segment

Roads

- State Routes 1, 9, 35, 84, and 92 are critical access routes for rural communities in western San Mateo and Santa Clara counties. For planning purposes, it should be assumed that all of these routes may have one or more major closures.
- I-280, which runs parallel to the fault source, may also be affected by this earthquake. Many highways and roads near the fault source are also susceptible to landsliding.
- The local roads in the eastern portions of San Mateo County and along the southern Hwy. 101 corridor will probably only experience scattered road closures. The 101 corridor from the San Francisco Airport north to Marin County is more vulnerable.

Bridges

- The San Mateo, Dumbarton, and Bay Bridges are key links between the heavily impacted areas on the Peninsula and the East Bay. For planning purposes, it should be assumed that these bridges are closed, at least for a few days. In addition, emergency planners should expect that approaches to these bridges, as well as local roads feeding the bridges, will be affected.
- The Golden Gate and Richmond bridges, as well as southern approaches to the Benicia-Martinez Bridge, may also be affected by this earthquake.
- In addition, non-retrofitted local roadway bridges on local roads should be considered a weak link along transportation routes.

Airports

- San Francisco and Oakland International Airports, as well as the Half Moon Bay and Palo Alto airports, are likely to be affected by road closures servicing their facilities. However, the Half Moon Bay Airport services an area that may be isolated except for this facility. Therefore, this airport could serve as a point of delivery for emergency supplies.
- Alternative air facilities at San Jose International Airport, Moffett Field, and other smaller airports (such as San Carlos) may be more accessible. Therefore, minimally affected airports should plan for increased air and vehicle traffic, both immediately and long term, should the major airports be impacted.

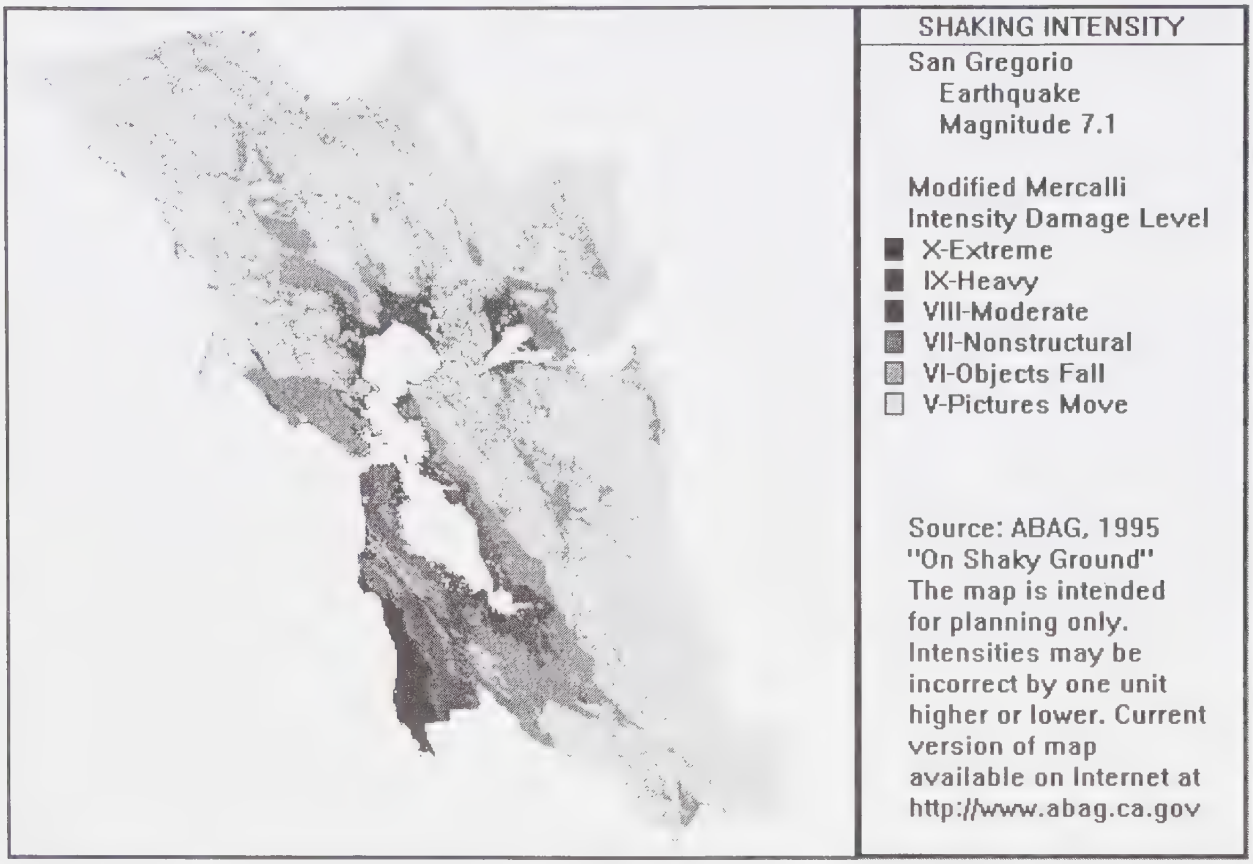
Ports

- The Ports of Oakland and San Francisco are expected to be affected by road closures after an earthquake. Oakland's facilities for large container ships are non-redundant in the immediate Bay Area. The Port of Kobe, Japan, experienced similar impacts following the Hyogo-Ken Nanbu earthquake in 1995. These facilities may be able to unload ships but not transport cargo out of the impacted area immediately following the earthquake. Other ports, such as Richmond, Redwood City, and Benicia, may not be as affected, but do not have equivalent facilities.
- Ports in southern California and along the entire west coast may experience increased shipping traffic should these ports be heavily impacted by an earthquake.

San Gregorio Earthquake Impacts

The Scenario

This scenario earthquake is for a magnitude 7.1 earthquake on the San Gregorio fault in San Mateo County.



Distribution of Closures

An earthquake along the San Gregorio fault would cause approximately ***216 road closures***. Almost half of these forecasted closures are predicted to be within San Mateo County (48%) and 25% are predicted to be within San Francisco. The distribution of closures is similar to the Peninsula San Andreas scenario, with the total closures being lower and significantly more concentrated within San Francisco and San Mateo counties; in combination they account for almost three quarters of the total closures.

It is important to note the differences in the types of closures that we are predicting. While in San Francisco over half of the closures are expected to be generated by building damage, in San Mateo County over two thirds of the closures are expected to be due to fault rupture and landsliding.

TRANSPORTATION SYSTEM CLOSURES DUE TO AN EARTHQUAKE ON THE SAN GREGORIO FAULT

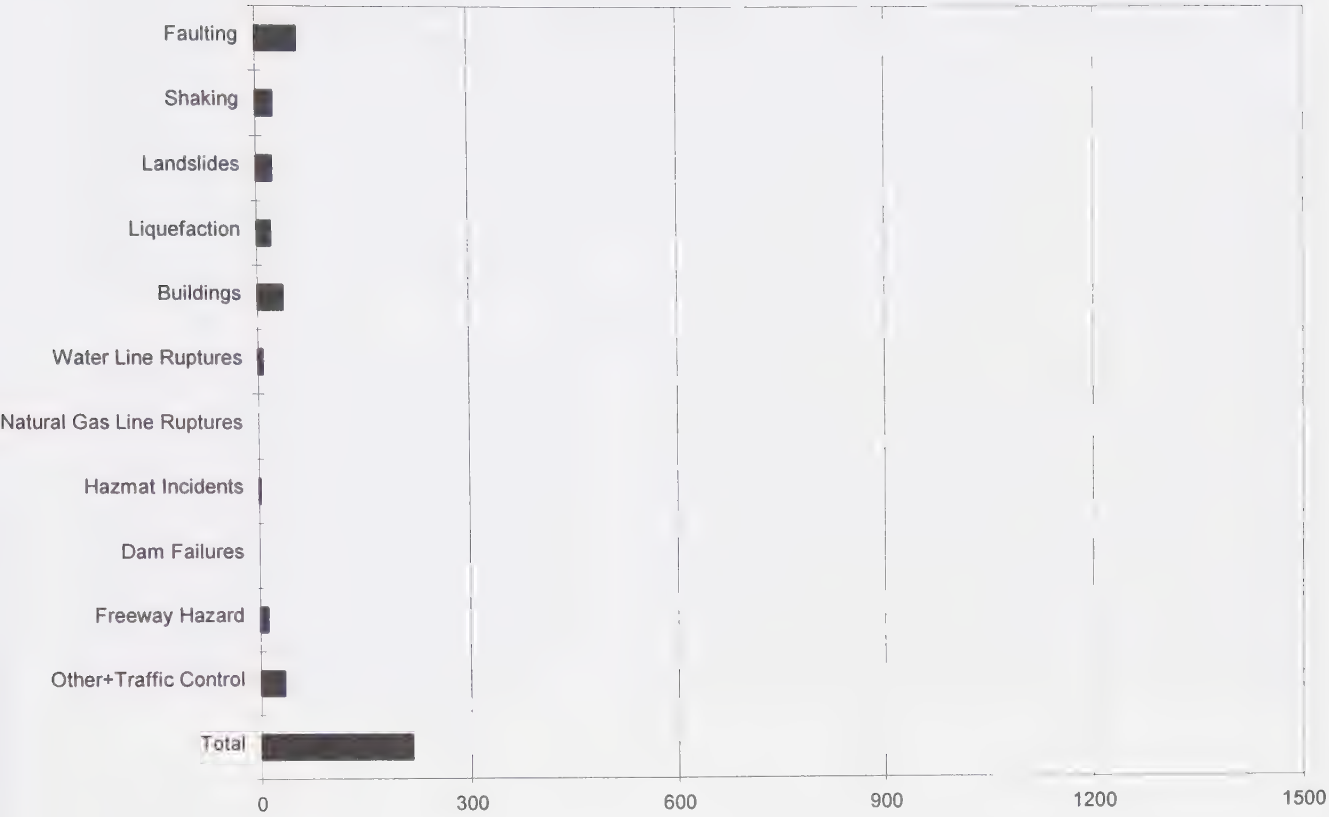
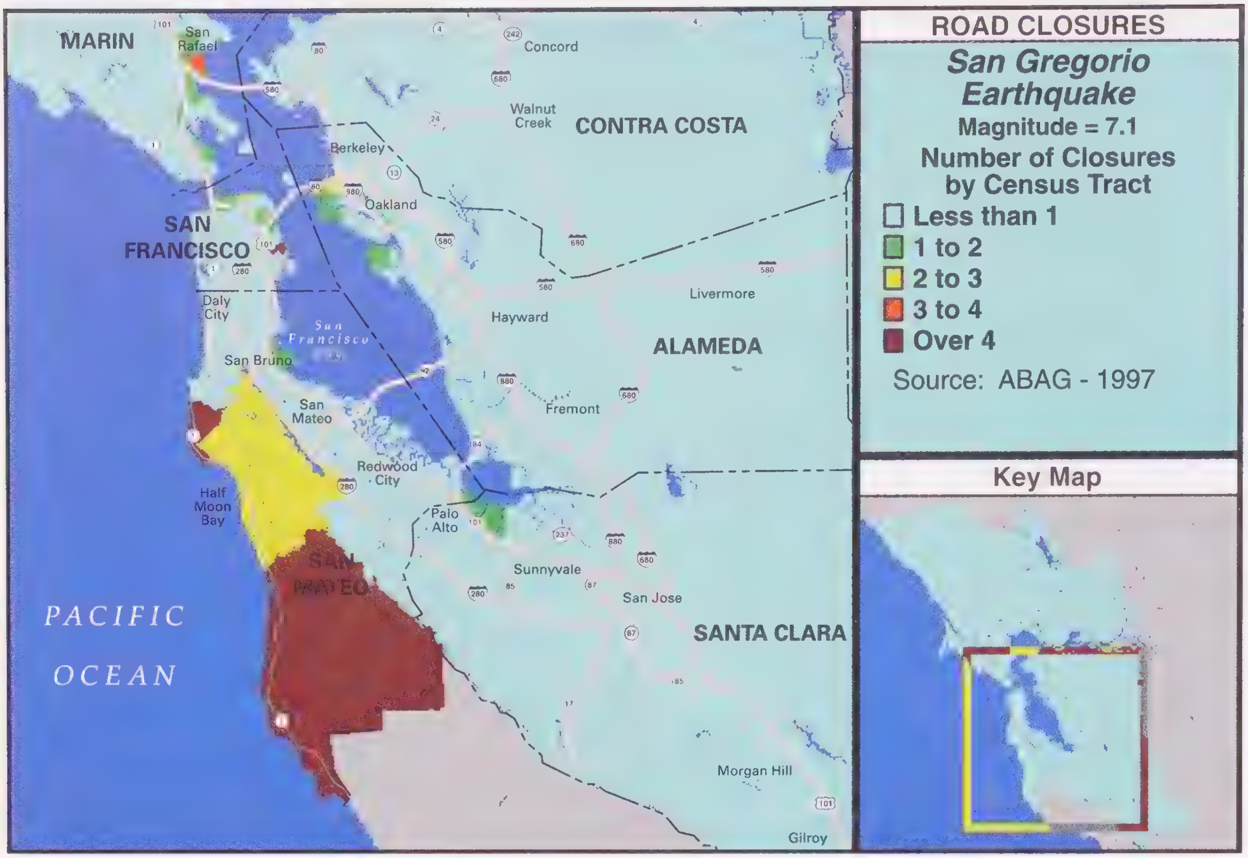


TABLE 33: Transportation System Closures by Hazard Type and County

Hazard Type	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	TOTAL
Faulting	0	0	0	0	0	58	0	0	0	58
Shaking	5	1	4	0	3	7	3	0	0	24
Landsliding	1	1	5	0	2	11	2	0	1	23
Liquefaction	4	0	7	0	7	2	1	0	0	20
Buildings	3	0	1	0	31	1	0	0	0	36
Water Line Ruptures	1	0	1	0	1	4	1	0	0	7
Natural Gas Line Ruptures	0	0	0	0	0	1	0	0	0	1
Hazmat Incidents	0	0	0	0	0	0	0	0	0	2
Dam Failures	0	0	0	0	0	0	0	0	0	0
Freeway Hazard	2	0	2	0	2	3	1	0	0	11
Other	3	0	4	0	9	16	2	0	0	34
TOTAL	20	3	23	0	55	104	10	0	1	216



Concentrations of Closures and General Planning Implications

As can be seen from examining the above map, most of the closures are expected to occur along the southwest side of the San Mateo peninsula. The rural areas around San Gregorio, Pescadero, and La Honda are expected to experience severe damage. Some of the key connectors within this area are State Route 1 and State Route 84. It is important to note that these roads are not redundant and that access to some of the rural communities along them might be severely impaired.

Within San Francisco, most of the disruptions to the local transportation system are expected to occur in landfill areas adjacent to the Bay. The high urban density of these areas coupled with their soil type make zones which are highly susceptible to earthquake damage and to disruptions in the local street network caused by indirect hazards.

TRANSPORTATION SYSTEM CLOSURES DUE TO AN EARTHQUAKE ON THE NORTHERN SEGMENT OF THE HAYWARD FAULT

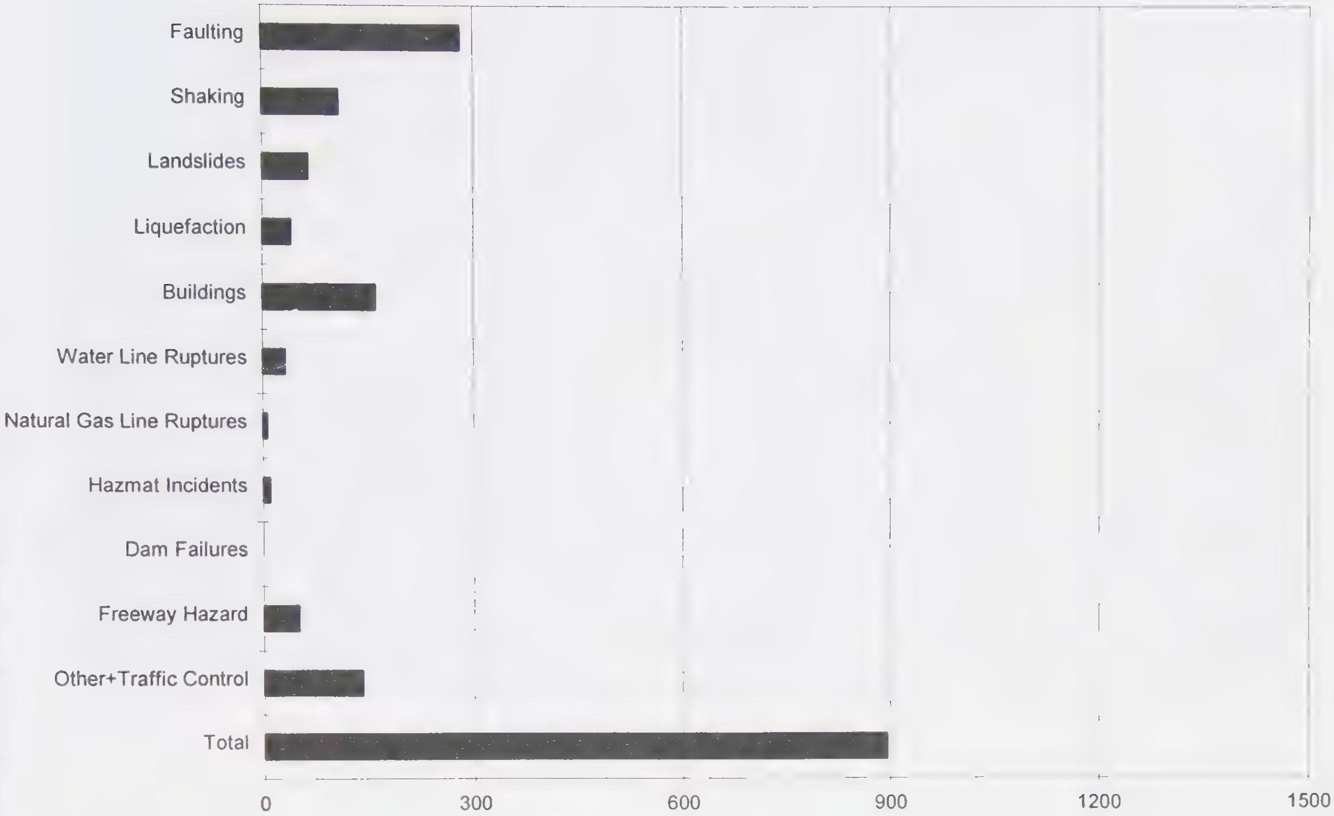
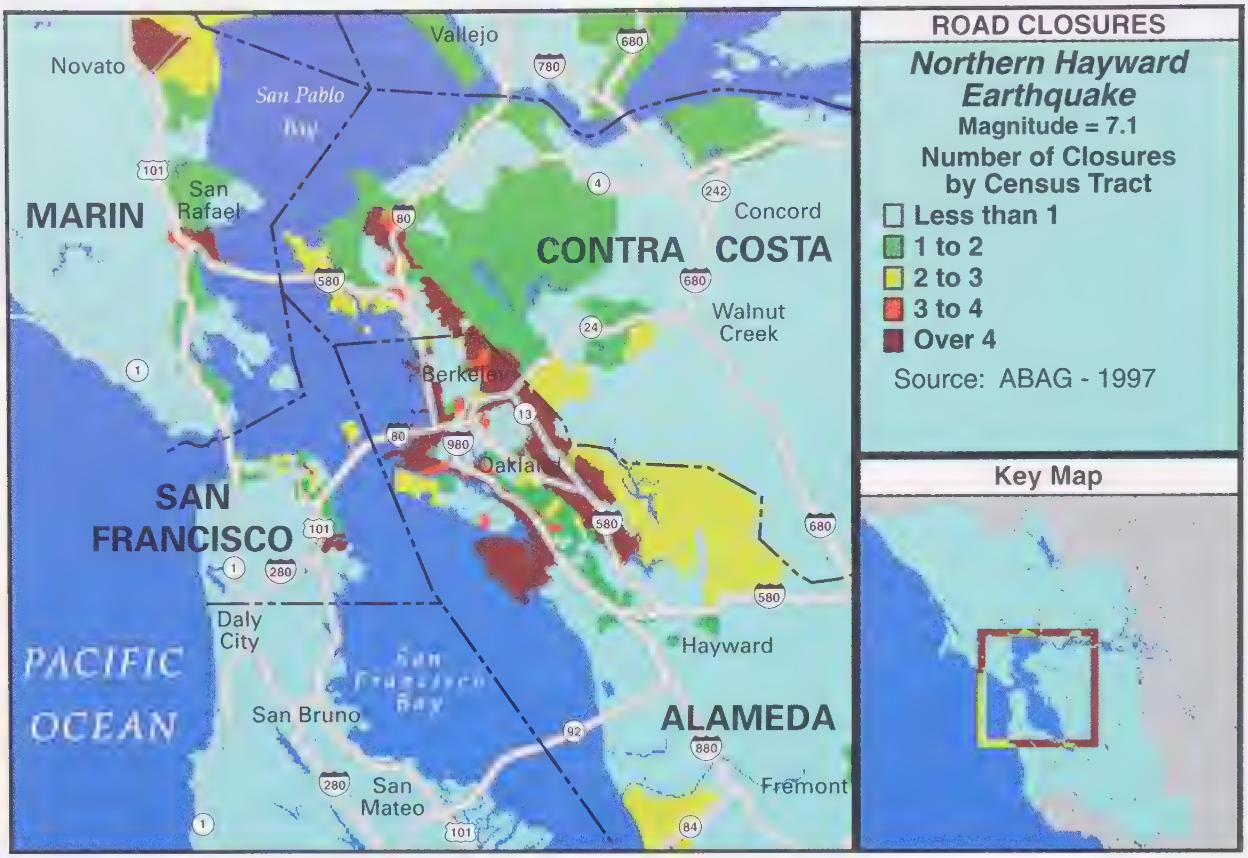


TABLE 34: Transportation System Closures by Hazard Type and County

Hazard Type	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	TOTAL
Faulting	169	113	0	0	0	0	0	0	0	282
Shaking	67	17	13	0	5	3	5	0	1	109
Landsliding	27	18	8	1	3	3	2	1	4	65
Liquefaction	12	4	10	0	7	1	1	4	2	41
Buildings	95	8	1	0	54	0	0	0	0	160
Water Line Ruptures	17	8	1	0	1	0	1	1	1	32
Natural Gas Line Ruptures	3	2	0	0	0	0	0	0	0	6
Hazmat Incidents	5	2	1	0	0	0	0	0	0	10
Dam Failures	0	0	0	0	0	0	0	0	0	0
Freeway Hazard	31	8	6	0	2	1	2	0	0	50
Other	79	33	7	0	13	2	2	1	2	140
TOTAL	506	213	47	2	85	10	14	8	10	894

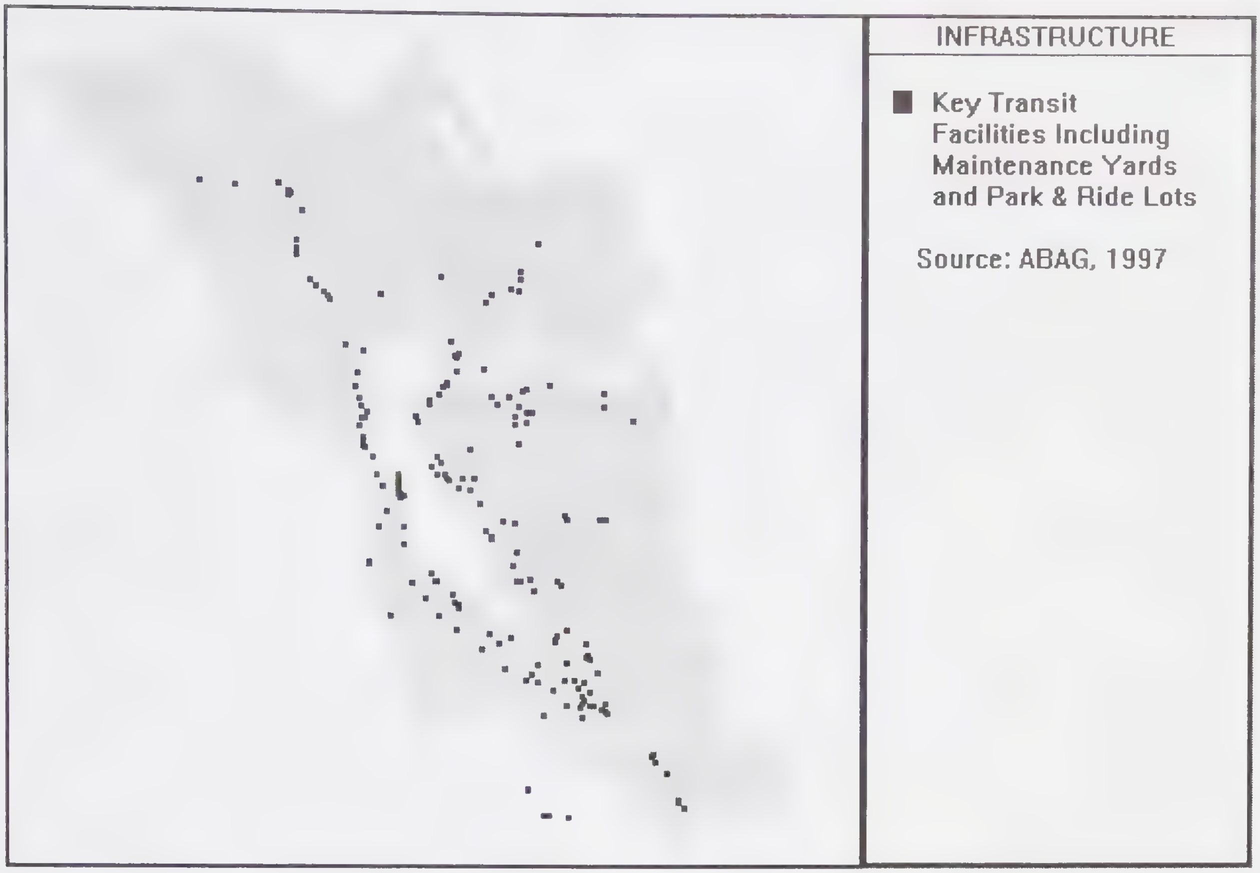
MAP OF PREDICTED ROAD CLOSURES



Concentrations of Closures and General Planning Implications

As can be seen from examining the above map, most of the closures are expected to occur along the east Bay. Two zones are expected to have the most severe transportation disruptions: the zone immediately adjacent to the fault along the 580 corridor and the zone immediately adjacent to the Bay along the 880 corridor. While these north-south connectors may not be fully operational, there should be alternatives available through the local street network.

While it has not been within the scope of this project to predict the performance of individual structures, the effect on the Bay Area's toll bridges is expected to be serious. It should also be noted that in most cases these bridges are not redundant and that thinking about alternatives in the event that they are not fully functional is critical.



Bay Area Transit Facilities

Experience in the Loma Prieta Earthquake

No major problems occurred with the bus system maintenance and repair facilities as a result of the Loma Prieta earthquake.

References

RIDES, Inc., 1993. ***The Bay Area Commuter's Survival Guide***: RIDES Inc., San Francisco, California, 29 pp.

Written and oral communication with Nancy Okasaki, Metropolitan Transportation Commission, Nov. 1996.

Emergency Health Care Facilities

Introduction

Bay Area's health care is provided in a variety of medical institutions, including full-scale hospitals, local health clinics, convalescent centers, mental health clinics, nursing facilities, abortion clinics, surgery centers, hospices, dialysis clinics, and drug-treatment centers. However, the region's acute-care hospitals are the primary facilities used for both immediate- and intermediate-term care following an earthquake. An acute-care hospital is a medical facility which provides general medical services, and which offers intensive care, surgery, an emergency room, and a capacity for at least 99 patients (Toppozada and others, 1994). The distribution of the 93 acute-care hospitals in this region is shown in the following table.

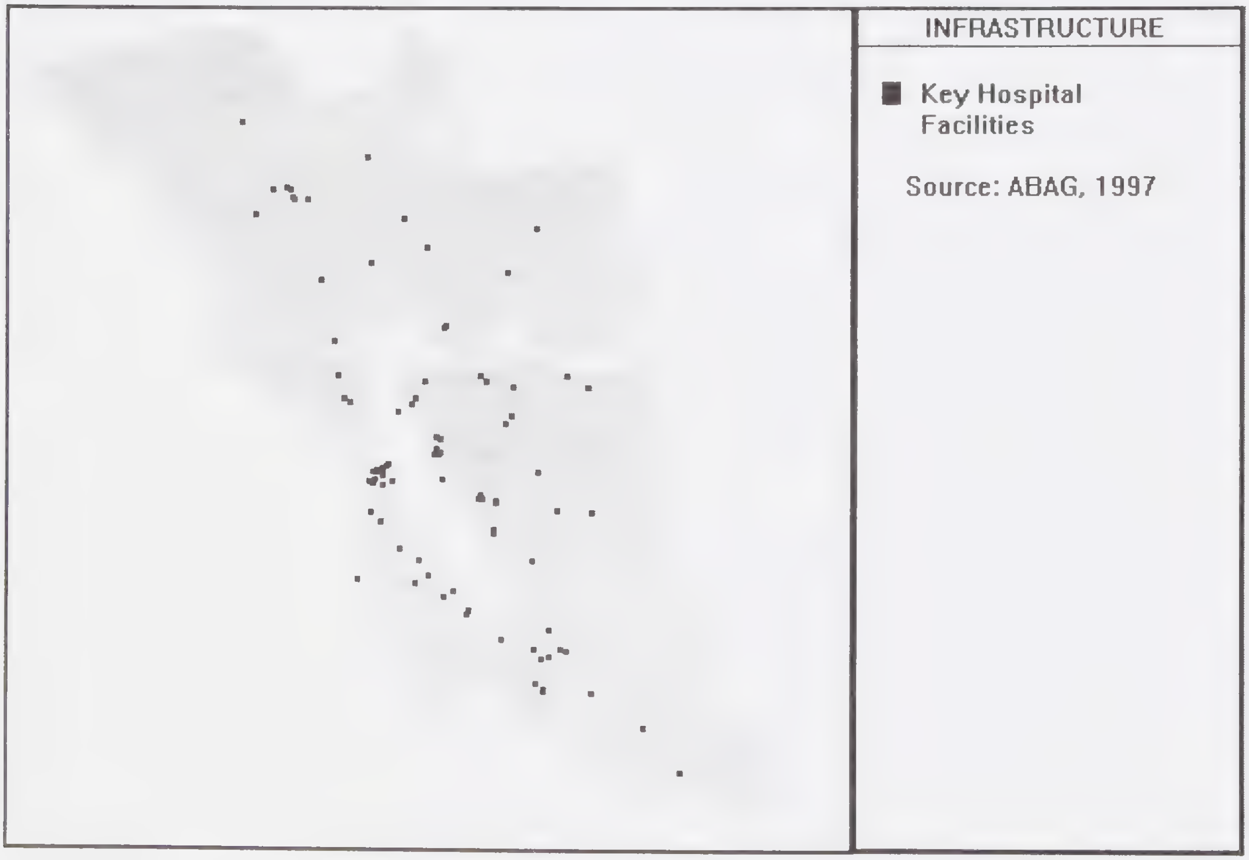
TABLE 28: Number of Acute Care Hospitals by County

Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma
18	13	4	3	17	9	15	4	10

Location of Emergency Health Care Facilities

This map depicts 93 mapped emergency health care facilities in the Bay Area, including:

- 8 hospitals which are designated trauma centers
- 84 community hospitals
- 1 military hospital



Bay Area Emergency Health Care Facilities

Past Earthquake Experience

Background

After the San Fernando earthquake of 1971, California lawmakers passed the Hospital Seismic Safety Act of 1972 to increase performance standards of structural design. Due in part to this law, hospitals have performed well in recent earthquakes.

During the Loma Prieta and Northridge earthquakes, response by hospitals was generally quick and thorough, but some problems did arise. ***Of greatest concern from a transportation planning standpoint were problems experienced by ambulances and paramedics gaining access to areas with injured people or returning to medical facilities. Restrictions to emergency health care response primarily involved heavy traffic on some arterials and a high degree of activity at some hospitals.***

Loma Prieta Earthquake

Overall, hospitals performed well structurally during the Loma Prieta earthquake. Although a few of these buildings experienced interruptions to elevator service or minor system damage, all remained operational. A few other hospitals lost administrative offices or out-patient clinics, but in all cases primary hospital services were not halted. Elevator service interruptions were due primarily to the activation of seismic motion detectors. However, about 18% of the stalled elevators reported in hospitals in the region were damaged and had to be repaired before their service could be resumed.

During the Loma Prieta event, Watsonville Community Hospital in Santa Cruz County was probably the hardest-hit of any hospital. Initially, commercial power and telephone services both were lost, and backup equipment did not perform; both emergency generators failed, as one fell on top of the other, and hand-held radios failed as well. The power loss affected rooms and hallways, the operating room, and the parking area. Water was not available for any purpose. Some equipment important to hospital operations lost function–liquid oxygen and autoclaves were not available. Shattered glass littered hallways and walkways. As has been observed in other earthquakes, many chemical spills occurred in the laboratory.

As a result, patient treatment was affected in this hospital immediately following the event. Aside from the difficulties with standard care and medical decision making, equipment could not be sterilized, communications with other hospitals was greatly reduced for a time, tracking of patients was nearly impossible, and needed portable oxygen tanks were not available. The ingenuity of hospital workers solved many of these problems, but not without large numbers of personnel on site. ***Also necessary was a capability to transfer patients by helicopter and automobile. In this case, hospital services depended much more on transportation networks than was imagined.***

In other parts of the Monterey Bay Area, communications problems again greatly affected emergency response of medical personnel. In Santa Cruz County, telephone lines were jammed

and radio conversations were so prolific that they confused ambulance drivers. There was little coordination at first as ambulance dispatchers had drivers criss-crossing routes. Finally, an ambulance supervisor was brought in and separated the types of calls given to fire departments and paramedics. Similarly, in San Benito County, communications breakdowns were big hurdles. Communications equipment toppled over in the basement of that county's EOC. The 9-1-1 system failed, and communications with hospitals were not possible until ham radio operators assisted. The communications system in Monterey County was out for ten minutes, and often jammed with calls. As in San Benito County, ham radio operators attempted to pick up the slack, but there was no link for these radios to the EOC, and the operators were not trained in basic medical terminology.

Problems of a scale similar to those experienced by the Watsonville Community Hospital did not occur in the San Francisco Bay Area.

In San Francisco, enough ambulances were on city streets to cause tracking problems, especially when computers went down. Both 9-1-1 and fire dispatch services were also down at times. There were communications problems from mutual aid companies, as multiple radio systems were unable to establish a common link. In Alameda County, the dispatch center did not take over immediately, and both ambulance and fire services were dispatched on their own for the first hour. The county hospital did not have proper hookup of their emergency radio and thus did not have communications outside their building for several hours.

On the peninsula and further south, communications problems were the main difficulties. In Santa Clara County, ambulances could not communicate with hospitals to determine operational status, and communications with incoming helicopters were also absent. As was true elsewhere, the dispatch center in San Mateo County had difficulties with its emergency radios, inter-ambulance communication was poor, and patient documentation was very limited.

Northridge Earthquake

In the Northridge earthquake, similar problems arose in hospitals. Facilities were hindered by the loss of commercial utilities. In most cases, affected hospitals lost power and communications; in general, backup systems worked better than in Loma Prieta, with generators and radio systems working well. Two hospitals experienced emergency power losses, but due to water leaks shorting electrical switches rather than equipment malfunctions. Success of backup systems was attributed to periodic and regular exercise of emergency response plans and equipment prior to the event.

References

California Office of Statewide Health Planning and Development, database of heath care facilties (1994 version) received 9-23-96.

Earthquake Engineering Research Institute, May 1990. "Loma Prieta Earthquake Reconnaissance Report" in ***Earthquake Spectra***: EERI Supplement to v. 6, Oakland, California, 448 pp.

Earthquake Engineering Research Institute, April 1995. "Northridge Earthquake Reconnaissance Report" in ***Earthquake Spectra***: EERI Supplement C to v. 11, Oakland, California, 523 pp.

Topposada, T.R., Borchardt, G., Hallstrom, C.L., Youngs, L.G., Gallagher, R.P., and Lagorio, H.J., 1994. ***Planning Scenario for a Major Earthquake on the Rodgers Creek Fault in the Northern San Francisco Bay Area***, California Division of Mines and Geology (CDMG) Special Publication 112, Sacramento, California, 249 pp.

Fire, Police and Emergency Operations Centers

Introduction

Fire and police response, as well as emergency coordination, are part of initial response operations following a natural disaster.

Fire departments respond to fire, medical, rescue, hazardous material and other emergencies on a 24-hour basis using the highway and local street system. Concerns of fire department personnel include fire control and prevention, a pre-hospital care system, public education, and effective emergency scene management. Emergency response often entails operations teams. These may include a hazardous materials response team or an urban search and rescue team. Generally, hazardous materials technicians, paramedics (with, in some cases, ambulances), and firefighters make up operations teams.

While cities may have different procedures regarding law enforcement officers, police usually play an important role in emergency response. Most cities and counties can dispatch police through their Emergency Operations Centers (EOCs). The Incident Command Systems (ICS) organization often establishes the local police as the lead agency, and requires the department to set up a command post. This allows the police to take a stronger response role than would be possible in a chaotic situation. Police presence is vital in areas requiring perimeter control, crowd control, and traffic control. These circumstances are common after significant earthquakes. In many cases, a police department also provides control over the press and other media. ***These functions all depend heavily on access to problem areas via local streets and the definition of areas by local streets.***

Pre-event response planning is crucial for smooth operations following a disaster. Specific policies should outline roles for each agency to follow during recovery. Thus, response planning should involve coordination among departments, such as police, fire, building, public works, and safety. The Emergency Operations Center becomes important in this coordination function. It is entrusted with coordinating response immediately following the disaster. Information flowing from this command center needs to be received by all involved agencies so that it can be passed along to the public as necessary with minimal confusion.

Police and fire stations, as well as EOCs, are critical in communications and in the meeting and dispensing of people even though the vehicles themselves do not need to return to these facilities between response events. Because many emergency response personnel live at significant distances from these facilities, the transportation links surrounding these facilities become even more critical.

The following sections describe the locations of these facilities, as well as problems associated with them following the Loma Prieta and Northridge earthquakes.

Regional Resources

Fire Stations

ABAG has cataloged 506 fire stations in the ten-county region. Of these, 93 (18%) are county stations and 413 are city or local stations. In many jurisdictions, more than half of the annual alarms are for emergency medical response.
Fire stations are distributed throughout the region as follows:

TABLE 29: Number of Fire Stations by County

Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	Santa Cruz
86	67	27	18	42	57	94	33	63	19

Police Stations

A total of 103 police stations have been cataloged over nine counties. Of these, nine are county stations and 94 are established by city police.

TABLE 30: Number of Police Stations by County

Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma
15	19	12	6	1	20	13	8	9

Emergency Operations Centers

An emergency operations center (EOC) has been established in each of the ten counties in the region. In addition, two supplemental facilities are present in both San Francisco and Alameda counties. Under the Standardized Emergency Management System (SEMS), the operational area EOCs have the primary responsibility for coordinating all of the response and recovery activities within each county. Some of these facilities are established by service organizations by joint powers agreements among cities in proximity to one another. Organizations involved in emergency services agreements usually include selected city and county departments, local medical groups, hospitals, schools, the Red Cross, and other public and private agencies.

Primary to their services is the maintenance of area emergency plans and the provision of training to emergency response teams. These groups may sponsor other projects, including hazardous materials response and creative communication systems.

Many of the agencies which operate these emergency centers practice periodic simulations. When a disaster occurs, EOCs use information they collect to assess the circumstances and set response priorities. They act as the points of coordination for multi-agency response. Mutual aid may be requested by the County through the California Governor's Office of Emergency Services, once an assessment of damage and understanding of resources needs is accomplished.

Regional Emergency Response

Disaster operations are designed to be initiated at all jurisdictional levels – municipal, county, state, and federal. Response of this type require the following:

- communication;
- status and needs assessment;
- mobilization of people and equipment;
- task performance based on a prioritization scale; and
- feedback, based on actions taken and changing needs for the purpose of reassigning priorities as necessary.

Location of Fire, Police and Emergency Operations Centers

This map depicts 599 mapped fire, police and emergency operations centers in the Bay Area, including:

- 487 fire stations
- 103 police and sheriffs offices
- 9 county emergency operations centers

Bay Area Police, Fire and Emergency Operations Centers

Past Earthquake Experience

Loma Prieta Earthquake

In the Loma Prieta event, success varied among fire, police and emergency operations. For the freeway collapse in Oakland, independent communication of the problem was rapid. However, interagency communication limitations slowed coordination among agencies, beginning with disruption of telephone communications and continuing with jammed radio frequencies. Needs were assessed by first responders, which in this case were emergency personnel from the city of Oakland. Key to mobilization success was the request of assistance by local organizations and the acceptance by county and state agencies, as well as cooperation by private companies located near the freeway structure. Without mutual aid agreements in place, interagency coordination would have been difficult. Part of what made the interdisciplinary approach possible was the presence of representatives from all coordinating agencies in the Command Post decision structure. Each agency was aware of both its responsibilities and the resources of other organizations. ***Luckily, the road network enabled essential personnel to gather at this Command Post.***

Not all areas requiring response assistance experienced similar success. In many parts of the Bay Area, the biggest problem among responders was poor communications. There were difficulties with dispatching fire departments, ambulances, and paramedics in at least three of the primarily-affected seven counties. Santa Clara County experienced problems with communication among hospitals, ambulances, and helicopters for emergency medical response. In two of the counties (San Francisco and San Benito), the 9-1-1 system had service breakdowns.

Many jurisdictions reported problems communicating between EOCs and field personnel. Clearly, planning at some EOCs was not satisfactory, in terms of adequate space, established command charts, and both interagency and intragency communications. Some EOCs unfortunately became media centers rather than designating media information hubs away from response activities.

The Oakland Office of Emergency Services was expertly run by city staff, who worked with the Red Cross on establishing emergency shelter and coordinating volunteers. The Oakland Police Department did well in establishing perimeter control around the collapsed freeway viaduct. It also designated media representatives to provide proper press relations. Crowd control was more difficult at that site, and combined with lack of training and checklists, first responder preparations by the Department were probably inadequate.

Elsewhere pre-planning was not complete. There was no system established to pull in damage reports, so damage assessment was spotty. Also, media calls contributed to jammed phone lines because no staff was dedicated to this task. However, the Governor's Office of Emergency Services responded quickly to requests from both Oakland and San Francisco for personnel and equipment.

In San Francisco, the EOC was too small to accommodate all of the department and response staff. This, coupled with communications difficulties, did not allow for a coordinated emergency response among city departments (police, fire, building and safety, and public works). Problems arose because of communications limitations, as the police controlling access to damaged areas in the Marina district did not feel as if information was being sent to them for passing on to local residents. Police were unprepared to perform damage assessments.

Northridge Earthquake

Because the Northridge earthquake occurred more than four years after the Loma Prieta earthquake, and state and federal agencies took actions based on lessons learned from that earlier event, disaster planning was more complete, and response activities faster, than what occurred prior to and during the 1989 earthquake. Local response agencies learned many lessons from the civil unrest of 1992 as well as the 1993 wildfires, including interdepartmental coordination and cooperation, and were able to apply these lessons to the Northridge event.

In the aftermath of the Loma Prieta earthquake, eight urban search and rescue teams were established by the California Governor's Office of Emergency Services and FEMA, each with 56 trained personnel. Six of these were sent to southern California to assist in post-Northridge operations soon after the event. Much of the initial search and rescue at sites with significant damage was done by local volunteers.

Damage assessment was undertaken by local governments, with mutual aid assistance. Additional inspectors came from the Structural Engineers Association of California, the American Society of Civil Engineers, the American Institute of Architects, the American Construction Inspectors Association, and the U.S. Army Corps of Engineers. The Department of Building and Safety for the City of Los Angeles doubled its staff of inspectors within a week to inspect over 80,000 buildings. In Santa Monica, inspectors were teamed with another city employee who had knowledge of city regulations. In many cities, the majority of the damaged buildings were inspected more than once.

Although sufficient emergency medical resources were available, some communications disruptions occurred which were similar to what was experienced during Loma Prieta. Failure of ambulances and the L.A. County Hospital to communicate, as well as unreliable radio systems at hospitals making up the Hospital Emergency Administrative Radio network resulted in fire captains being dispatched to hospitals for damage assessment. In addition, federal response dispatched eight Disaster Medical Assistance Teams of 50 medical care providers to the regional EOC, and selected hospitals and clinics to increase medical personnel available to affected areas.

While the experiences of response personnel were generally better than that of Loma Prieta, there were signs that improvements were still necessary. The Regional EOC did not have adequate preparations for emergency power, and lost electrical service for several hours. Flooding from water main breaks affected the Los Angeles EOC, and some communication links were not operable. Requests by local jurisdictions for additional resources were in some cases duplicated and in others did not go through subsequent governmental levels before local resources were

exhausted. Some of the smoothness in administrative management, at both the state and federal levels, may have been due to politics, as the event occurred at the beginning of an election year.

Conclusions Based on Past Earthquake Experience

The experiences in these past earthquakes all emphasize the problems with communication systems. Each time a communication system fails, response vehicles use limited transportation resources less efficiently. Also, each communication system failure means that repair and maintenance personnel need to use transportation links to gain access to these facilities to bring parts and equipment to repair the communication system.

References

Earthquake Engineering Research Institute, May 1990. "Loma Prieta Earthquake Reconnaissance Report" in ***Earthquake Spectra***: EERI Supplement to v. 6, Oakland, California, 448 pp.

Earthquake Engineering Research Institute, April 1995. "Northridge Earthquake Reconnaissance Report" in ***Earthquake Spectra***: EERI Supplement C to v. 11, Oakland, California, 523 pp.

Written and oral communication with all cities and counties in the project area regarding location of fire and police facilities.

Public Mass Care (Feeding and Shelter)

Introduction

Although agencies other than the American Red Cross (Red Cross) and local governments are involved in disaster sheltering, feeding and the bulk distribution of relief supplies, the Red Cross and local governments are officially designated with that responsibility.

Administratively, in the nine-county Bay Area, the Red Cross is divided into six chapters: the American Red Cross Bay Area chapter which covers Alameda, Contra Costa, San Francisco, San Mateo and Marin counties; Santa Clara County San Jose chapter; Santa Clara County Palo Alto chapter; Solano County chapter; Napa County chapter; and the Sonoma County chapter.

The American Red Cross Bay Area chapter is the "North Coastal Zone Lead" for disaster Services, providing disaster resource coordination and support for relief operations in coastal chapters from the Oregon border to the Southern edge of Monterey County. While emergency planning and response principles apply to all five Red Cross chapters, administratively they function as separate units of the national organization.

Over time, the Red Cross's emergency response operation is divided into three phases: emergency response, recovery, and, additional assistance. During the emergency response phase, the relief effort concentrates on establishing detailed damage assessment, providing emergency shelter, food, clothing, and medical assistance. The recovery phase concentrates on getting displaced families out of shelters and into temporary or transitional housing and helping families restore a more normal life style. The additional assistance phase takes place months or even years following a disaster. This phase is designed to help affected residents who have disaster caused needs that are not completely addressed by all other assistance programs.

Functionally, Red Cross's relief activities can be divided into three main aspects which could, potentially, take place during any of the three phases of the response operation described above:

- **Direct Services** which involves the provision of services to disaster clients, including Mass Care, Family Services, Disaster Health Services and Disaster Welfare Inquiry.
- **Support Services** which involves maintaining and delivering the necessary emergency relief supplies from warehouses and trailers around the Bay Area to centers where direct services are being provided. It also involves communication, accounting, staffing of local disaster volunteers, disaster computer operations, records and reports, human and government relations and the provision of damage assessments.
- **Administration and Coordination** which involves the overall management for Red Cross operations.

Mass Care depends on the delivery of emergency supplies to shelters, service centers, and feeding locations using the transportation network. The initial response is particularly dependent on the ability to communicate and to quickly move critical supplies and personnel.

Functional communications are essential for efficient distribution of supplies, coordination of relief efforts and the effective use of limited transportation facilities.

Direct Services

The delivery of service to those affected by the disaster occurs in a number of field facilities including shelters, fixed or mobile feeding sites and service centers. While most facilities used by the Red Cross are pre-identified, the actual site(s) used are determined at the time of the disaster based on the situation. ***The Red Cross chapters in the Bay Area maintain relationships with hundreds of potential shelter sites to provide the maximum location flexibility whenever a disaster occurs. Unfortunately, this requires that all shelter support equipment and supplies must be moved to the shelter site, once a site selection has been made.***

Shelters

Shelters are places where the affected population can sleep, eat, and receive disaster related information as well as medical and mental health care. They are the primary site where people displaced by the disaster can seek refuge from the elements and have their basic human needs met. While shelter sites are occasionally co-located with Red Cross service centers, shelters are always assumed to be a fixed feeding site because the people being housed and the staff are fed at the site.

The Red Cross normally designates public schools as potential shelters because they are strategically located within a community, because they are designated by state statute as emergency shelters (Katz Bill of 1984, AB 2786 - Sec. 40041.5, Education Code) and because they typically have facilities suitable for shelters. While the Red Cross does not own designated shelter sites, they enter into "statements of understanding" with the facility owners/managers.

In addition to public schools, the Red Cross has statements of understanding with community centers, churches, universities and trade organizations so that, depending on an area's need, these facilities might also be utilized as a shelter or other service delivery site.

Any particular school may, depending on the area's need, be designated as a shelter, a fixed feeding site or a service center. Red Cross guidelines for shelter space suggests a minimum of 40 sq. ft. of sleeping space for each individual. Under ideal conditions, most school sites used as shelters have a capacity of 300-500 residents. In addition, the actual number of people being served at the site is sometimes doubled because of people camped in motor homes and campers in the shelter parking lot, using the shelter for food, showers, information and other services.

Available space and accessibility are two of several primary criteria for shelter site selection. Shelter sites need to be located as near as possible to the pre-disaster homes, schools and employment of the affected population. In addition, the sites need to be accessible both in terms of serving people with disabilities and also in terms of public transportation. Since shelter users simply "show up," these facilities need to be in visible and accessible locations. Signs therefore play an important role in announcing the location of shelters and emergency relief services

within a disaster area. There are often creative ways of doing this; during the Northridge earthquake, shelters were marked with balloons. ***While the Red Cross will put up signs and markers, as well as work with a local public transportation provider to improve access to their disaster relief facilities, typically the users go to shelters on their own.***

Feeding Sites

The Red Cross establishes feeding programs not only at their shelters, but often at additional fixed sites or at roving or mobile routes. For these, specially designed vehicles called emergency response vehicles (ERVs) are utilized. A non-shelter fixed feeding site may be established to support emergency workers or a neighborhood where the utilities have been disrupted. These feeding sites are often established at the local churches, community centers, fire stations or other public buildings.

Mobile feeding routes are established to bring food, water, cleaning products and other basic supplies to areas where emergency workers or affected residents are performing rescue or clean up work. The mobile feeding program can allow the disaster relief effort to continue, without the lost time involved if workers had to be transported out of the affected area to be fed. ***In order to be effective, mobile feeding routes are dependent on a functional transportation network in and out of the disaster affected areas.***

Service Centers

Service Centers consist of places where disaster victims can seek social-economic assistance. Through case workers in its service stations, the Red Cross tries to best meet the needs of each disaster victim. Typically they are facilities established during the "recovery phase", when people are trying to move out of emergency shelters and back into their homes or transitional housing. Service centers usually open as soon as the damage assessment and the logistics of site selection and set up are completed, typically 5-7 days after the disaster. Individuals or families affected by the disaster are interviewed to establish their recovery needs and resources. Once these needs are established they are given purchase orders (called disbursing orders) for assistance ranging from rent, rent and utility deposits, basic furniture, occupational and medical supplies, and minor home repairs.

Support Services

The Red Cross distributes a variety of relief supplies, ranging from bottled water to clean up supplies to plastic sheeting. Like the feeding program, bulk distribution can be either delivered from fixed sites or by mobile routes using rental vehicles. The Red Cross has the capability of deploying much of their relief equipment in the form of mobile trailers or kits. In the Bay Area, there are over 40 trailers strategically deployed with the supplies required to open up a disaster shelter. The trailers vary in size from those designed to support a 100 people shelter to those designed to support up to a 1,000 people shelter. The trailers are generally located at secure sites such as fire and police stations and corporate yards. In addition, the Red Cross has mobile generators (80-100 kW), fuel trailers, communications van, a trailer mounted communication

tower, and, is planning a job headquarters supply truck that will contain all of the administrative supplies, office equipment, fax and computer equipment to set up an off-site emergency operations center.

Food can be obtained locally by the Red Cross from a variety of sources depending on the specifics of the disaster. Some of these include: a fixed or mobile kitchen operated by either the Red Cross or the Southern Baptists; a catering company such as an airline caterer; a local hotel or restaurant; a local school. In-kind donations of food and other related supplies is another source for both raw food, snack and beverages.

In addition to these sources, the Red Cross maintains open accounts with most of the major food wholesale companies, like Sysco, Rykoff-Sexton, Kraft and Nestle Foods. Since these food suppliers are often located in out-of-the-way places, the Red Cross has predesignated staging areas around the Bay Area for use in establishing a distribution system during a disaster. The Red Cross also has statements of understanding with Moffett Airfield in Sunnyvale to use part of their facility as a material or staff staging area. In addition, the Red Cross is eligible to use USDA commodities for disaster feeding. These are normally acquired from a local school food program and then restocked by USDA following the disaster.

Since the Red Cross does not "stockpile" food, beverages or other feeding supplies, they are dependent on the ability to quickly move large quantities of supplies to their shelters and other service delivery sites. Disruptions to the transportation system will cause significant problems with shelter service delivery. Until access is restored to shelters and the warehousing sites that supply them, availability of food, water, medical and sanitation supplies will be limited to what is available from the community adjacent to the shelters. The distribution of supplies both from these external food suppliers to the Bay Area, as well as from the Bay Area centers to individual shelters and mass feeding centers, rely on a reasonably functional transportation system.

Administration and Coordination

In addition to the provision of direct services and the support of these services, administrative facilities for coordinating are required. The most common coordination facility are central and district "job headquarters" (EOCs). The Red Cross has a number of "statements of understanding" with organizations which have facilities suitable for relief operation job headquarters. These range from the University of San Francisco, the Oakland Masonic Lodge, Hayward centennial Hall to the Clarion Hotel in San Mateo.

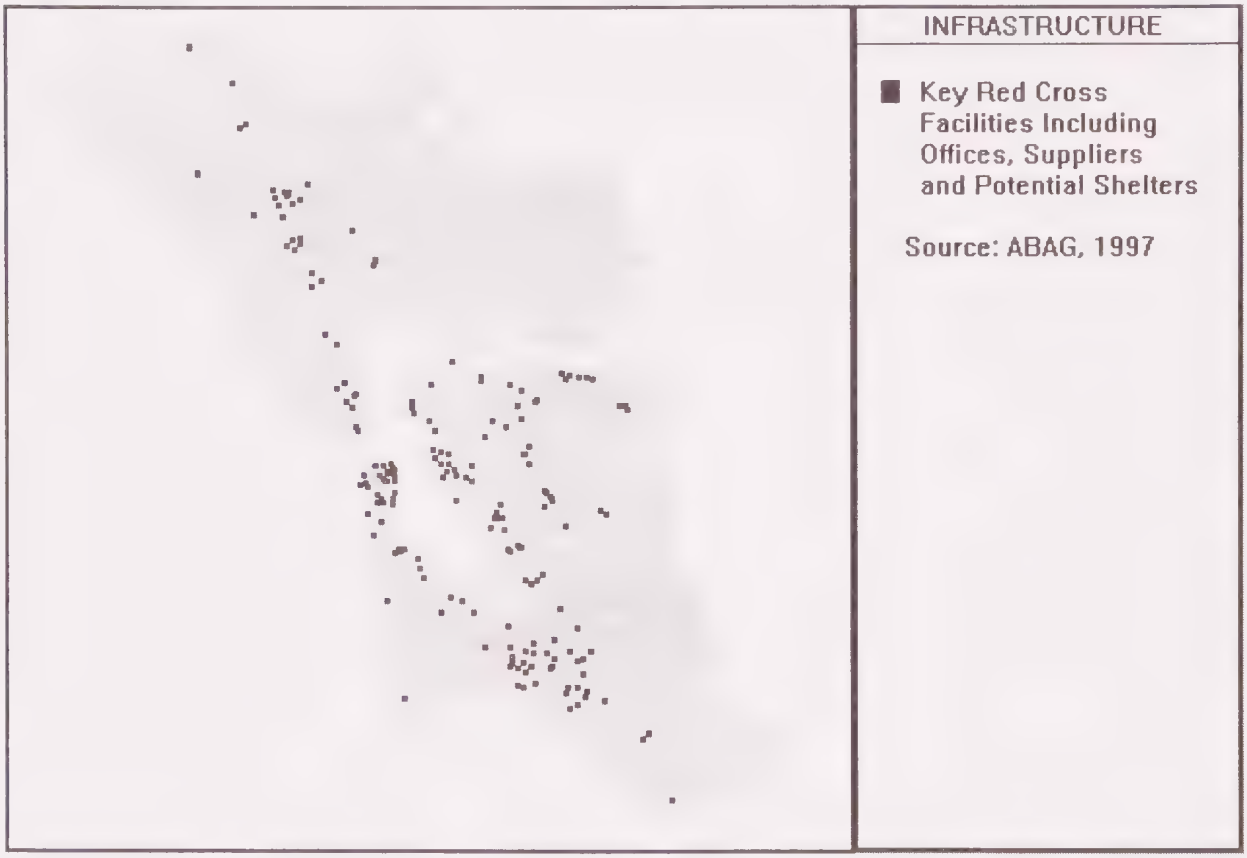
A job headquarters needs to be in constant communication with personnel in the shelters and those delivering supplies to them. In order for the relief effort to run smoothly, there are continual updates on the demand for services at shelters, service centers and mass feeding stations so that job headquarters can properly direct resources to where they are most needed, as well as on ***the conditions of the regional transportation network used for delivery of those supplies***.

Typically activities during a relief operation are controlled and coordinated by a management team headed by a "Job Director" who supervises all aspects of the relief operation and assistant directors and officers who are in charge of specific functions of the relief operation.

Location of Potential Public Mass Care Facilities

This map depicts 204 mapped potential public mass care facilities in the Bay Area, including:

- 174 potential shelter locations
- 9 potential food suppliers
- 8 alternative Red Cross Headquarters
- 13 Red Cross Zone/Chapter locations



Bay Area Potential Public Mass Care Facilities

Past Earthquake Experiences

In both the Loma Prieta and Northridge earthquakes a similar number of shelters in their predesignated locations were opened: a total of 45 Red Cross shelters after the Loma Prieta earthquake and a total of 41 Red Cross shelters after the Northridge earthquake (not including four that were opened by the Salvation Army after Northridge). Data from the Northridge earthquake indicates that indoor shelter population peaked approximately one week after the earthquake when the number of individuals seeking shelter peaked at 15,000 (Perkins and others, 1996). Similar data from the Loma Prieta earthquake indicates that a total of 4,665 people were housed by Red Cross shelters (Harrald and others, 1992).

In addition to the indoor shelter facilities, informal outdoor shelter in locations such as public parks, parking lots or front yards were common after both earthquakes. After the Northridge earthquake, officials in Los Angeles estimated that approximately 20,000 people were sleeping in these informal outdoor locations. Similarly after the Loma Prieta earthquake, an emergency tent city was set up for people displaced in a downtown Watsonville park. It is apparent from this course of events that many individuals prefer to remain near their possessions and damaged homes rather than being relocated to temporary shelters which might not be immediately accessible to their dwellings.

The pattern of outdoor "informal sheltering" seems to have been problematic for public officials. In both Loma Prieta and Northridge it was difficult for city officials to provide sanitation and protective services to a widely dispersed population, raising many concerns about threats to public health. Due to this issue, public officials began a large-scale effort to move individuals from the informal outdoor shelters into either official indoor shelters or back into their homes. In addition, for those preferring to remain outside, official "refuge centers" were set up by the Red Cross. The efforts to move individuals from the informal outdoor settings was successful; 18 days after the Northridge earthquake, these had all been closed while 27 indoor shelters housing 3,500 remained open.

The Loma Prieta and Northridge earthquakes both illustrated the difficulty of providing effective emergency response when normal communications and transportation systems are disrupted. During the first hours following Loma Prieta, the Red Cross units in the Bay Area were unable to effectively communicate with each other. Movement of critical supplies and personnel were delayed by a combination of lack of knowledge of priorities (created by lack of effective communications systems), disrupted transportation routes and in the next few days, and traffic jams created by the loss of vital commute routes.

Since the Loma Prieta earthquake, the local Red Cross has invested heavily in new communications systems, deployed large amounts of shelter supplies on trailers and installed additional back-up power. Following the Northridge and Kobe earthquakes, local chapters of the Red Cross initiated a joint planning project with the state and national sectors of the Red Cross to produce an integrated response plan for major Bay Area earthquakes. When completed later this year, the plan will be used to model other Red Cross earthquake response plans on the West Coast.

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Water Supply Facilities

Introduction

In the Bay Area, water for domestic use is provided by a large array of local service companies. Approximately 130 agencies supply water to the multitude of cities, towns, and unincorporated communities throughout the Bay Area. These water agencies range in size from the East Bay Municipal Utility District, which services all or parts of twenty cities in two counties, to more than a dozen very small private companies serving specific local developments in unincorporated areas. Water agencies may be municipally owned, or they may be county water districts, special districts, community service districts, mutual water companies, or private water companies.

The Water Supply and Distribution System

Sources of domestic water include runoff from the Sierra Nevada range, water flows from the river system of the Central Valley, water collected in local reservoirs from creeks and streams, and water pumped from wells.

Water is transported from distant sources through four major aqueducts serving the Bay Area – the Mokelumne, Hetch Hetchy, California, and South Bay. Water transported by the first two originates in the Sierra Nevada, and by the latter two from the Sacramento-San Joaquin delta.

Next, it is pumped to an array of both open and closed storage reservoirs, often using large diameter mains. Water in open reservoirs is then supplemented by water collected from creeks and streams. There it is usually pretreated and pumped and/or gravity-fed to their customers, through mains and transmission lines to local districts. Pumping plants provide water pressure to areas that pressure cannot be supplied by gravity flow alone. These plants are dependent on power for their operation. ***Finally, thousands of miles of distribution pipes are used to deliver water to individual customers. These pipelines are typically located along streets.***

Agencies may sell water to their customers as retailers or wholesalers, depending on their sources and the structure of their water supply contracts.

Location of Water Supply Treatment Plant Facilities

This map depicts 52 mapped water supply treatment plant facilities in the Bay Area.

Past Seismic Experience

Loma Prieta Earthquake – San Francisco Bay Area

From the Loma Prieta earthquake, no damage was reported to the four major aqueducts serving the Bay Area. On one of the embedded cylinder prestressed concrete pipelines of the San Felipe Project supplying the south Bay (the Santa Clara conduit), a joint pulled apart and water was lost

Bay Area Water Supply Treatment Facilities

until the segment was closed off. The other segment of this line was used then to carry all of the allotted water for that area.

Of the several dozen dams and open reservoirs within the region, one experienced significant damage and two suffered minor damage from the Loma Prieta earthquake. The minor cracking at Anderson and Lexington Dams did not threaten the storage of water, and was readily repaired. On the other hand, damage to the Lake Elsman Dam (owned and operated by the San Jose Water Co.) was significant, requiring rebuilding of the outlet structure and spillway. The repair work was completed the following year, but required that the capacity of Lake Elsman be reduced prior to the completion of the repairs.

No storage tanks were reported damaged in the north and central Bays, but three smaller tanks were damaged in the south Bay. An unanchored steel tank buckled, a redwood tank collapsed, and a large post-tensioned concrete tank ruptured along a vertical joint. One welded steel tank was drained when a connecting line to the tank separated from the tank's floor plate.

Although water treatment plants in most parts of the region were undamaged, equipment at two plants in the south Bay experienced some problems. At one, wave action (sloshing) from ground shaking and differential movement damaged three clarifiers. The plant operated at reduced capacity until the repairs were made. At the other affected plant, wave action damaged baffling

in the coagulation basins. This facility was shut down for repairs and water was supplied from wells. In both cases, power losses delayed restoration of water supply.

Most earthquake damage to water supply systems tends to be on transmission and distribution lines. Approximately 470 leaks to water mains in the Bay Area were reported after the Loma Prieta earthquake. In addition, 110 service connection breaks were reported for a total of 580 leaks. In the Bay Area, the vast majority of these leaks were in older developed areas along the shorelines of San Francisco Bay on geologic materials which tend to amplify ground shaking and are prone to differential settlement and ground failure.

In San Francisco, most breaks occurred in smaller (4-, 6-, and 8-inch) cast-iron pipes with fixed joints, and in areas exhibiting differential settlement. Approximately 150 of the 470 leaks in water mains occurred in this city, and over two-thirds of these were in the Marina District. Some of the Marina District breaks were in larger (20- and 30-inch) mains. Older pipes played a role in a large percentage of region-wide breaks, most of which were likely weakened by corrosion. Service connection breaks occurred primarily in lines made primarily of galvanized iron, copper, and polyvinyl chloride.

In the east Bay, the East Bay Municipal Utility District (EBMUD) reported approximately 135 leaks of the 470 total leaks in water mains. In Alameda, corrosion affected the joints of welded steel pipe, exacerbating leakage resulting from shaking and liquefaction.

In the south Bay, approximately 120 leaks occurred in mains of various sizes, ranging from 4 to 37 inches, and of steel, cast iron, ductile iron, and asbestos cement construction. More than half of these were in steel pipe no older than 30 years but had developed holes from corrosion. Other leaks were at pulled joints or associated with circular breaks.

Leaks in lines did have some affect on fire-fighting efforts. Although the San Francisco Fire Department has an independent water system, breaks in a dedicated line (for fire fighting only) south of Market Street, as well as hydrant damage, quickly drained a large storage tank. The tank was recharged with salt water in a matter of hours.

Problems with power interruptions limited the supply of water in some areas. As could be expected, pumping plants in the region reported no damage, but power losses to these and other facilities providing water ranged from several hours to several days. In San Francisco, eight pumping plants lost power, and the area for which these plants supply water had only enough low-pressure water for fire protection. Treasure Island lost power and water service was interrupted for three days.

Loma Prieta Earthquake – Monterey and Santa Cruz Areas

None of the water used in both the Monterey Bay and in the Santa Cruz areas is imported from the delta or mountains; it is all from groundwater wells or local reservoirs.

No reservoirs in this area leaked from Loma Prieta. All of the pumping plants and all but three wells in the two areas performed well; those wells which did fail filled with sand. Concrete basins at a filtering plant in Watsonville leaked and the facility was shut down, but that was the only plant south of the Bay Area which sustained damage other than to small equipment.

Ten mid- to large-sized tanks had problems in these areas. Two welded-steel tanks with wood roofs sustained damage at the roof connection, and two other tanks drained because of broken pipes for inflows and outflows. One welded-steel tank experienced a bracket failure which caused buckling. Five redwood tanks were destroyed.

A number of small private and mutual water companies, with limited equipment capacities, were devastated. Some tanks collapsed, piping both above and below ground broke, and power was lost for days. Equipment repair in and recovery of these little water districts took months.

At least 300 leaks occurred in mains (4-, 6-, and 8-inch pipes), due to both joint failures and pipe cracking. Also, the area experienced 320 service connection leaks, for a total of 620 leaks. Cast-iron pipe performed poorest, particularly those with leaded joints. Several leaks occurred in asbestos cement pipe in Watsonville, while this pipe performed well in the Hollister and Santa Cruz areas. In the Santa Cruz area, leaks occurred at the threads of galvanized pipes. Pipes 12 inches or less in diameter and in unstable soils had the most problems.

In Watsonville, because of the numerous breaks, as well as problems with both commercial and backup power, the water system could not remain pressurized. Customers were cautioned to boil water since contamination with the sewer system was possible (although never confirmed).

Northridge Earthquake

The Northridge earthquake produced damage patterns similar to those experienced in the Loma Prieta earthquake. Water supply systems overwhelmingly experienced damage in supply and distribution networks rather than at specific plants and facilities. Over 1,700 leaks were detected in areas affected by that earthquake. Water supplies were more affected by the Northridge earthquake than the Loma Prieta earthquake because several welded steel and prestressed concrete supply pipelines (54- to 120 inches) experienced cracks and compression bulges. In moderately-sized pipes (33- to 78-inch lines), welded compound bends broke, rubber gasket joints and mechanical couplings separated, and bell-and-spigot joints failed in both tension and compression. The smaller, primarily older, distribution lines failed. These lines were more likely to fail if they were of rigid cast-iron of corroded steel. Some valves and hydrants were also broken.

Conclusions Based on Past Earthquake Experience

Water supply agencies were responding to 1,200 leaks in water mains and service connections after the Loma Prieta earthquake. They were also responding to 1,700 leaks following the Northridge earthquake. Access to these thousands of leaks puts a far greater strain on the transportation system than accessing the few dozen specific facilities which were damaged in

those two earthquakes. Thus, unlike most other transportation users, water districts will need access to much of the street network.

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Wastewater Treatment Facilities

Introduction

Wastewater is collected through out the Bay Area by 127 sewage agencies, whose jurisdictions are arranged into districts. Sewage agencies collect wastewater, treat wastewater or do both. Several of the sewage agencies have wastewater treatment plants in their districts, but some do not. There are 74 wastewater treatment plants currently operating in 10 counties of the Bay Area.

The Wastewater Treatment System

Most sewage agencies collect or send wastewater to and from the treatment plants via pumping stations, lift stations, mains, laterals, and storage ponds in their districts. Most of the treated wastewater outflows to the bay or the ocean. Some of the agencies deposit treated wastewater into existing or specially created marsh lands.

Many of the sewage systems use gravity flow, and therefore do not require electric power and pumping stations. In addition, it is likely that water service will be unavailable; without water, waste water will not be collected through pipes and some pumping stations. Thus, the wastewater treatment plants are more essential following an earthquake emergency than the pipelines or pumping stations. In addition, ***all of the operators of the treatment plants stated that their plant would be their number one priority to access in the event of an earthquake, not the sewage collection system.***

Location of Wastewater Treatment Facilities

This map depicts 69 mapped wastewater treatment facilities in the Bay Area.

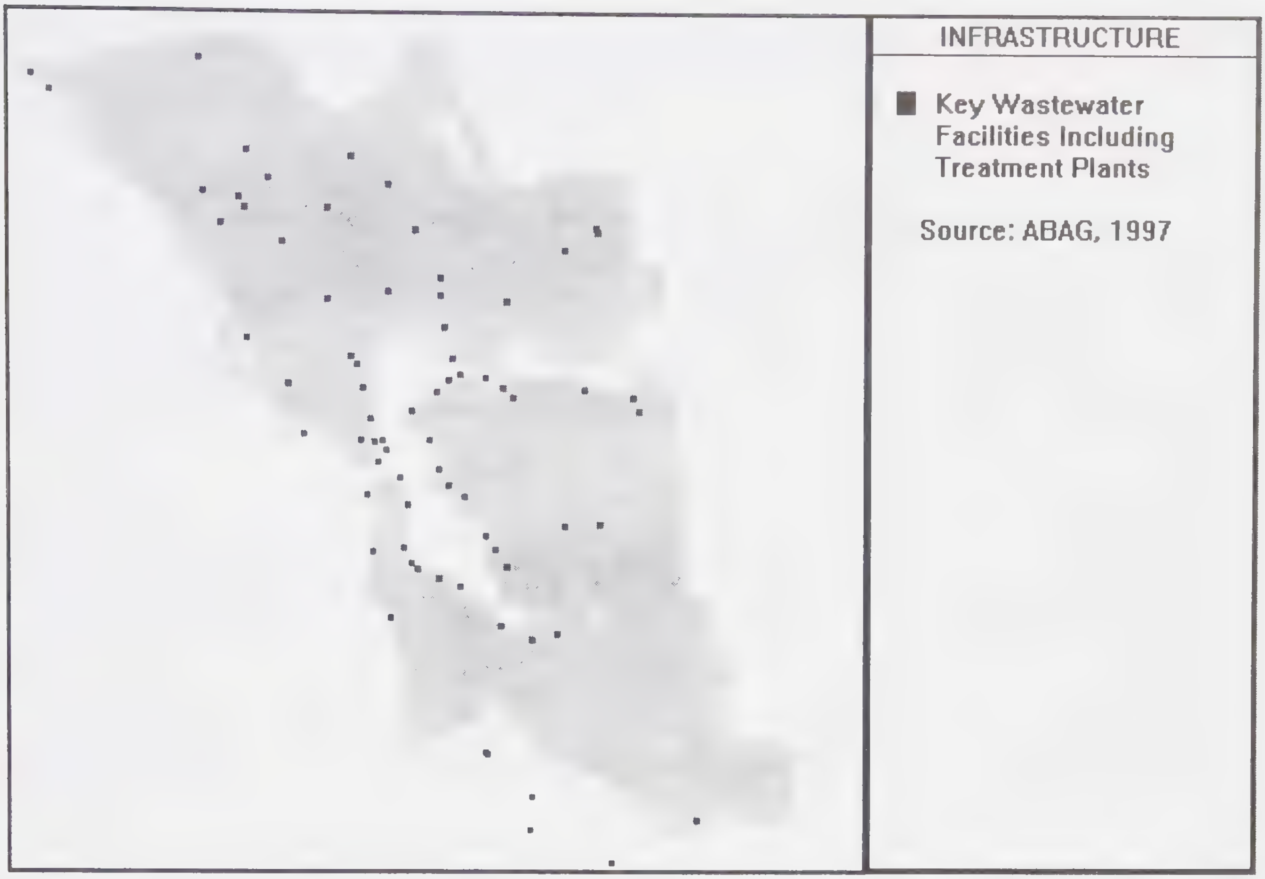
Experience in Loma Prieta

There were few sewer main breaks observed following the Loma Prieta earthquake because most sewage flows with gravity and wastewater does not appear on the surface of the ground. However, it can be assumed there were as many sewer main breaks as water main breaks where the ground is unstable. Sewage agencies are in the process of performing video camera surveys of mains to determine the extent of damage.

The most significant impact of the earthquake on sewage systems was the loss of power to facilities for several hours to several days. Breaks in sewer pressure lines (force mains) were discovered when power was restored.

Central Bay Area

A six-block area in Alameda experienced liquefaction and this caused damage to the sewer mains. This area is located on 1960s-era dredge fill.



Bay Area Wastewater Treatment Facilities

The regional wastewater treatment plants in San Francisco and Oakland displayed no major structural damage. However the loss of power caused the release of raw sewage into the Pacific Ocean and San Francisco Bay.

In Oakland. the regional plant lost power for seven hours. The plant's secondary activated sludge process was severely affected by the death of its biomass which was caused by a caustic chemical spill from an industry upstream. In one case sloshing sewage caused a wave motion that damaged a 12-inch cast iron roller guides and rotation of floating digestor covers. In addition, either the roller guide assembly anchorage failed or the wheel axles failed on most guides. (At a plant near Sacramento, 100 miles from the epicenter, similar problems occurred on four of the eight digestor covers.)

In San Francisco, most of the damage to the sanitary sewer system (which in this city includes both wastewater and storm water) involved frames around the catch basins and manholes. Additional damage included circumferential cracks in the 84- and 96-inch outfall lines and a leak in a pressurized 66-inch reinforced pipe with rubber gasket joints.

There were almost no impacts on users except in localized areas where there may have been minor blockages or loss of force-main pressure because of the power outage. In both San

Francisco and Oakland, discharge into the Bay could have been avoided with adequate emergency power supply and automatic start up of emergency generators.

South Bay Area

All the regional treatment plants maintained their structural integrity. At the Palo Alto Wastewater Treatment Plant, wave action from sloshing sewage caused the most damage to clarifiers; for example, scrapers were jammed by fiberglass scum troughs that fell into the clarifier. In addition, aluminum access covers on the roof of primary sedimentation basins fell into the basin when dislodged by the sloshing sewage. Workers got the plant back into operation within two hours.

The Alvarado Wastewater Treatment Plant, and South Bayside Wastewater Treatment Plant reported almost no damage to any of their facilities. Wave action tore lose some center-well fiberglass baffles in a couple of the clarifiers. At the Alvarado Plant a few superficial cracks were found in pipes. Lost commercial power was successfully restored by emergency generators. No leaks in the sewer system were detected.

The City of San Mateo Wastewater Treatment Plant reported damage to its multiple hearth sludge incinerator. Other damage reported was gas and water leaks, and damage to chlorine contact basin baffles.

Santa Cruz

The County Sanitation District collects sewage from developed areas of the county (except for the cities of Scotts Valley and Santa Cruz) and sends it to the Treatment Plant in the City of Santa Cruz. Most of the communities in the Santa Cruz Mountains have cesspools or septic tanks.

The most serious damage that was discovered at the regional plant operated by the City of Santa Cruz was several leaks in the county's force main where it separated at a joint. There was a release of 800,000 gallons of raw sewage in Santa Cruz because of power loss to the pumping stations for 30 to 35 hours.

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Electric Power Transmission and Natural Gas Facilities

Introduction

In the Bay Area, electric power is provided by one primary source – Pacific Gas and Electric Company. While future competition may change the supplier of electricity to the intermediate and end users, it still will be likely that the transporter of the power will be PG&E. The two cities which are supplied outside of PG&E, by the Western Area Power Administration, are Palo Alto and Alameda. This contracted power, however, is delivered over PG&E's network. PG&E supplies natural gas to the region for cooking, space heating, and water heating.

Power Generation and Distribution

PG&E's electricity-generating facilities consist of nine power plants in the Bay Area region, with the largest being the Pittsburg and Contra Costa plants along the shore of northern Contra Costa County and the Hunters Point plant in San Francisco. Other plants in the region are located in Sonoma County (The Geysers), San Francisco (Potrero), Alameda (Oakland), and Contra Costa County (Oleum and Martinez plants). Together these plants generate over 5000 megawatts. One of the larger plants in PG&E's service area that supplies electricity to the Bay Area is at Moss Landing (Monterey County), generating 2000 megawatts. At least ten cogeneration plants associated with industrial facilities also generate power within the region – for an additional 400 MW.

Electricity is transported via transmission and distribution lines criss-crossing the region. The transmission lines branch off from the main 500 kilovolt intertie system which links the utilities throughout the west coast. In addition, over 1000 substations convert high- and medium-level voltages (500 kV, 230 kV, and 115 kV) to medium- and low-level voltages (60 kV, and 24 kV to 4 kV) for local users.

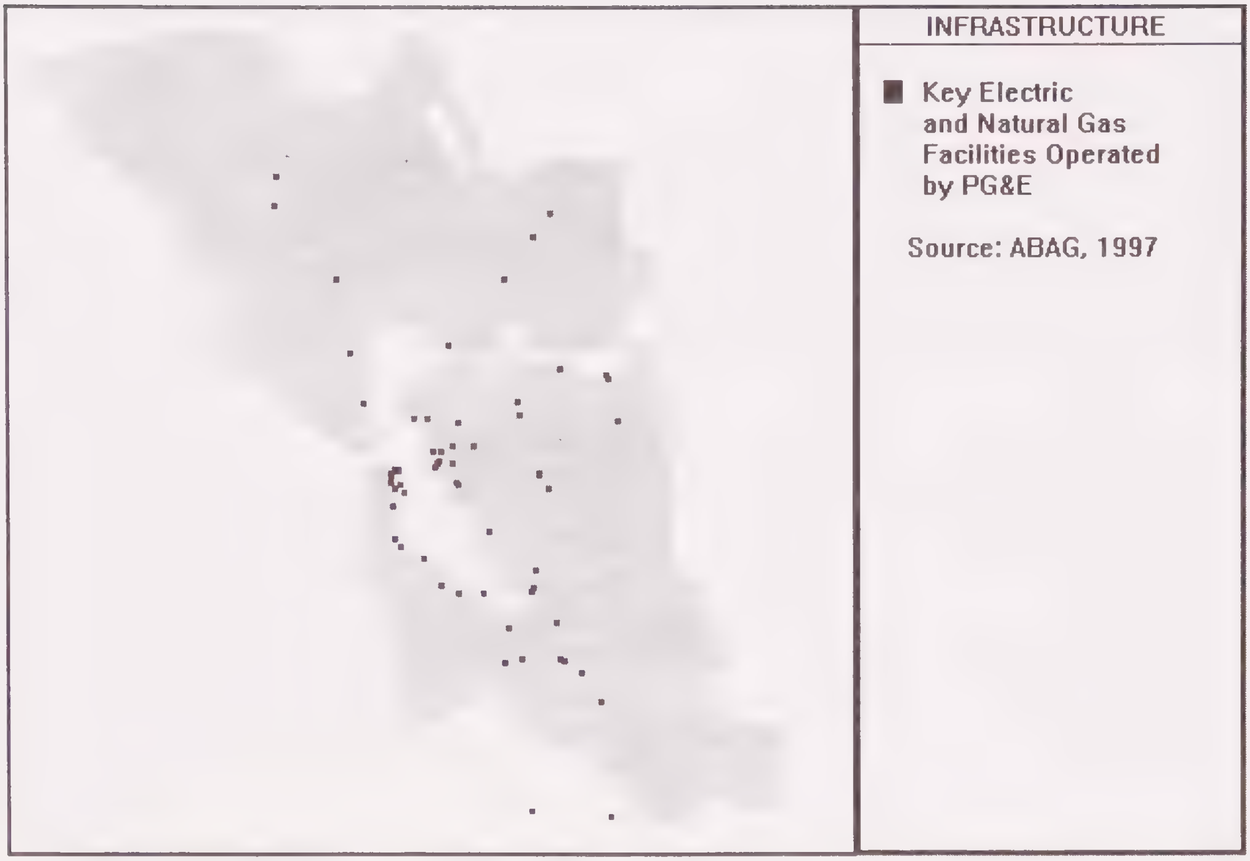
Natural Gas

Natural gas is supplied through a network of pipelines and storage fields, with large transmission lines importing gas across both the Oregon and Arizona borders. Approximately 300-500 gas valves act as control switches in the system. Both imported natural gas, and gas extracted from gas production fields, is piped under pressure in large transmission lines (12-26 inches) to underground storage fields and then distributed via thousands of miles of smaller lines (2-8 inches). As with water lines, these distribution pipelines are typically located along streets.

Location of Critical PG&E Facilities

This map depicts 49 mapped critical PG&E facilities in the Bay Area, including:

- 3 power plants
- 28 key substations
- 14 service centers
- 14 key offices or buildings
- 3 critical natural gas facilities



Bay Area Critical PG&E Facilities

Experience in the Loma Prieta Earthquake

Electricity

The two power plants in the nine-county Bay Area affected by the Loma Prieta earthquake were Hunters Point and Potrero. The former sustained only cracks in the boiler enclosure of one of the three units, in a shear wall, in some concrete, and in a pipe coupling link. Only a few bracing areas were damaged in the latter. Cogeneration facilities generally came through undamaged, even though many of them received significant shaking.

Outside the nine-county Bay Area, but close to the earthquake source, the Moss Landing plant sustained greater damage than the two just described. Restraints, hangers, and other supports broke, leaks in tubes and wind box damage to the boiler occurred, and a bearing failed on the turbine. Lack of anchors and failed pipe couplings affected water tanks, and leaks occurred in the gas supply to the boiler because of failures at pipe flanges. Total damage to the plant was over $4 million.

The most vulnerable parts of the electrical system were the transmission substations. Three Bay Area substations sustained major damage, and one other experienced minor damage.

Specific Planning Considerations

Northern Calaveras Earthquake

Roads

- The I-580 and I-680 corridors are the key routes in the impacted area. Multiple closures are expected along this corridor.
- Emergency response planners should also anticipate that the State Route 84 transportation corridors (including both the highway itself and the local streets along this route) will be affected by multiple closures.

Bridges

- The Benicia-Martinez Bridge is the most direct link between the heavily impacted area and the North Bay. For planning purposes, it should be assumed that traffic on this bridge may be impacted, at least for a few days. Emergency planners should expect that approaches to other Bay Area toll bridges connecting to the East Bay, as well as local roads feeding those bridges, will be affected by road closures.
- In addition, non-retrofitted local roadway bridges on local roads should be considered a weak link along transportation routes. Such bridges may be particularly problematic near the approaches to the Benicia-Martinez Bridge, and may impact bridge traffic even if the bridge itself does not fail.

Airports

- Emergency response planners should assume that Oakland International Airport will be affected by multiple closures of roads servicing its facilities after this scenario earthquake.
- Alternative air facilities at San Jose and San Francisco International Airports, Travis AFB, Concord's Buchannan Field and the Livermore Airport are expected to be more accessible. Therefore, these airports should plan for increased air and vehicle traffic, both immediately and long term, should Oakland International experience access difficulties.

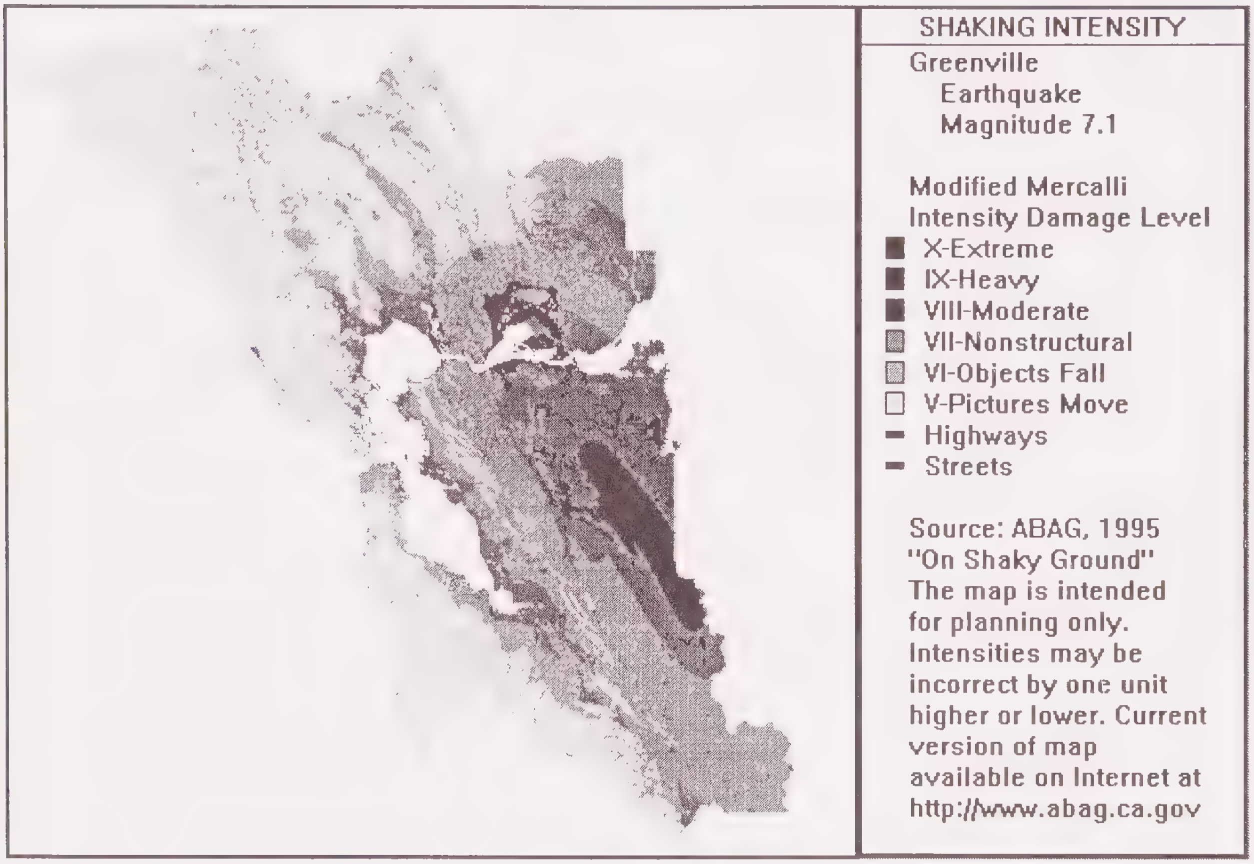
Ports

- The Port of Oakland is expected to be affected by several road closures after this earthquake. Oakland's facilities for large container ships are non-redundant in the immediate Bay Area. The Port of Kobe, Japan, experienced similar impacts following the Hyogo-Ken Nanbu earthquake in 1995. These facilities may be able to unload ships but not transport cargo out of the impacted area immediately following the earthquake.
- The Port of San Francisco, as well as other ports in southern California and along the entire west coast may experience increased shipping traffic should the Port of Oakland be heavily impacted by an earthquake.

Greenville Earthquake Impacts

The Scenario

This scenario earthquake is for a magnitude 7.1 earthquake on the Greenville fault in far eastern Contra Costa, Alameda and Santa Clara counties. This fault was the source of the Livermore earthquake.



Distribution of Closures

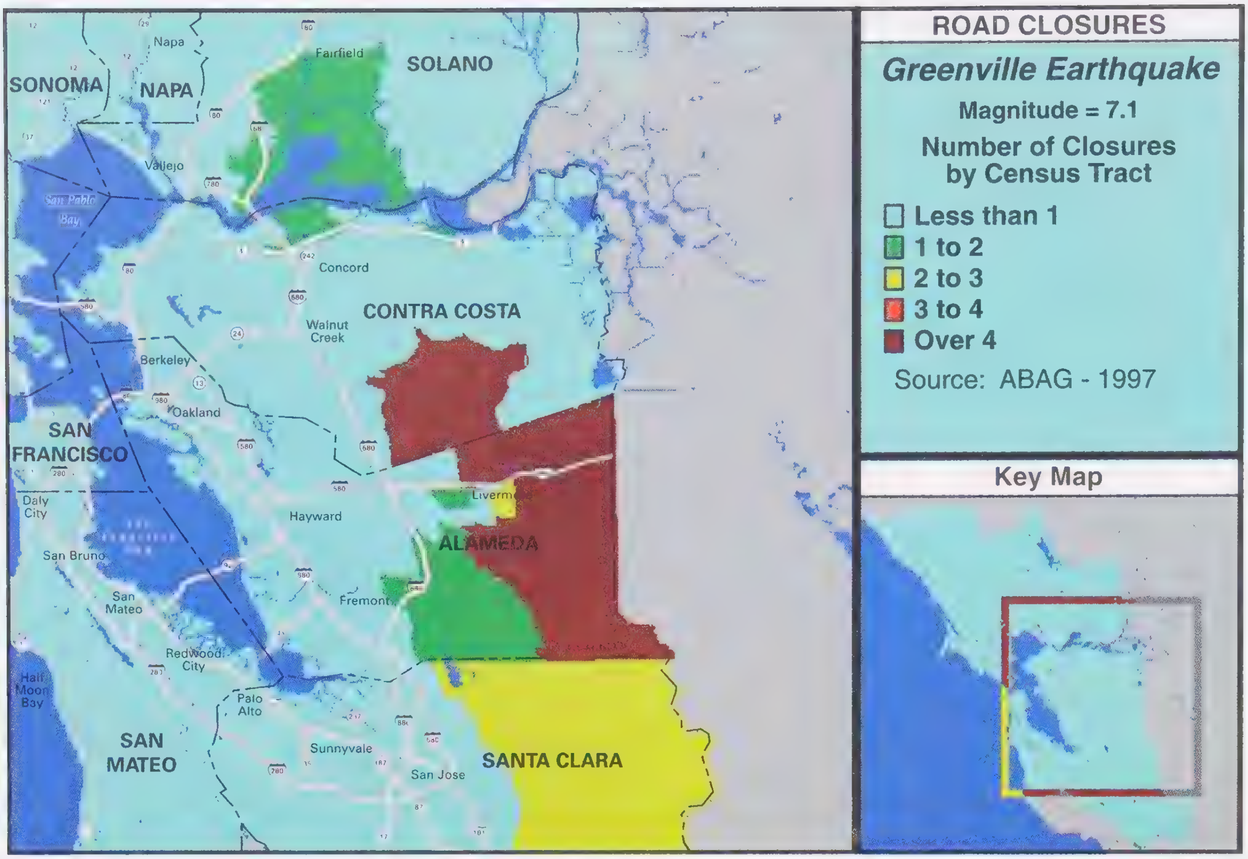
An earthquake along the Greenville fault would cause approximately ***124 road closures*** and would rank tenth in the number of closures out the eleven scenarios modeled in this report. Over half (51%) of these closures are expected to occur within Alameda County, while Contra Costa County is expected to experience one quarter of the closures.

The direct hazards of fault rupture, shaking and landsliding, are expected to be the most significant source of closures, accounting for over half (54%) of the total.

TRANSPORTATION SYSTEM CLOSURES DUE TO AN EARTHQUAKE ON THE GREENVILLE FAULT

TABLE 42: Transportation System Closures by Hazard Type and County

Hazard Type	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	TOTAL
Faulting	21	4	0	0	0	0	1	0	0	26
Shaking	12	5	2	0	1	1	2	0	0	23
Landsliding	6	7	0	0	1	0	2	1	0	18
Liquefaction	1	2	0	0	0	0	0	5	0	8
Buildings	3	2	0	0	3	0	0	0	0	8
Water Line Ruptures	3	3	0	0	0	0	1	1	0	8
Natural Gas Line Ruptures	1	1	0	0	0	0	0	0	0	2
Hazmat Incidents	1	0	0	0	0	0	0	0	0	2
Dam Failures	0	0	0	0	0	0	0	0	0	0
Freeway Hazard	6	2	1	0	0	0	1	0	0	10
Other	10	5	1	0	1	0	1	2	0	19
TOTAL	63	31	4	0	6	2	8	10	1	124



Concentrations of Closures and General Planning Implications

As can be seen from examining the above map, most of the closures are expected to occur along portions of eastern Alameda and Contra Costa counties. Transportation disruptions are expected along portions of the I-580 corridor as well as along rural sections of State Route 84. Areas within and around Livermore are expected to experience the largest concentrations of closures.

While this area presents large census tracts due to its rural nature, the roads connecting the small communities are few. In most cases, these roads are not redundant and access to some of the rural communities along them might be severely impaired.

Specific Planning Considerations

Greenville Earthquake

Roads

- The I-580 corridor is expected to experience multiple road closures as a result of this scenario earthquake, particularly of those routes crossing the fault source area west of Altamont Pass. These closures are of particular concern due to the lack of alternative arterials and its major role in freight movement.

Bridges

- It is unlikely that any of the toll bridges will be affected by road closures as a result of this earthquake.
- However, non-retrofitted local roadway bridges on local roads should be considered a weak link along transportation routes.

Airports

- It is unlikely that any commercial airports will be affected by significant road closures as a result of this scenario earthquake. However, the Livermore Airport will be impacted.

Ports

- It is unlikely that any port facilities will be affected by significant road closures as a result of this scenario earthquake.

General Conclusions

We can combine the information on road closures with these key transportation corridors to identify critical vulnerabilities in our current transportation system.

The results of this extensive analysis of the potential closures of roads, together with these key corridor segments, points to several vulnerabilities in our current transportation system.

- the south Oakland corridor segment in any of the three Hayward scenario events;
- the north Oakland/Berkeley/Richmond corridor segment in any of the three Hayward scenario events;
- the Bay Bridge and, particularly, its east-Bay approaches in all of the scenarios except the Maacama, West Napa, and Greenville earthquakes;
- the Peninsula corridor in the San Andreas Peninsula scenario earthquake;
- the San Mateo County coast corridor in the San Andreas Peninsula and San Gregorio scenario earthquakes;
- the tri-valley corridor in the northern Calaveras and Greenville scenario earthquakes;
- the northern I-680 corridor in the Concord-Green Valley and northern Calaveras earthquakes;
- the Richmond-San Rafael Bridge corridor in all of the scenarios except the Maacama, West Napa, northern Calaveras and Greenville earthquakes; and
- the Marin - 101 corridor in the San Andreas Peninsula, San Gregorio, three Hayward, and Healdsburg-Rodgers Creek scenario earthquakes.

What do we need to do next?

As a follow-up to this study, transportation providers and planning agencies need to:

- ☑ hold corridor-level and scenario-specific workshops to help identify ways to mitigate the anticipated transportation impacts; and
- ☑ identify critical transportation facilities that need to be usable, or returned to service, immediately following an earthquake, as well as to help initiate the necessary future planning and improvement actions.

What can we do now?

Both transportation providers and transportation users need to consider this study's estimates of road closures, and make appropriate preparations. Some suggested planning actions are supplied as checklists in Appendix A of this report for:

- ☑ transportation providers;
- ☑ utilities;
- ☑ emergency services providers;
- ☑ local governments;
- ☑ private companies; and
- ☑ residents.

APPENDIX A: CHECKLIST FOR PLANNING ACTIONS ...

Transportation, utility, and emergency service providers each should examine methods to keep providing transportation services or to plan around expected transportation interruptions.

General Checklist

Employees

- ☐ work with employees to set up alternative routes from their homes to your key facilities and offices in an emergency
- ☐ plan alternative shifts and/or crews since maintenance workers can be overworked
- ☐ cross-train employees to allow for some workers being unable to reach your facilities in a timely manner
- ☐ make efforts to ensure safety to crews working on repairs, for they may be close to other damage

Operations

- ☐ *roads* - work to keep open surface roads in and out of your facility routinely maintained by your agency
- ☐ *supplies* - ensure that you have stocked your operations center with food, water and sanitation systems to allow for disruptions
- ☐ *fuel* - connect fuel pumps at vehicle yards to a backup power system
- ☐ *fuel* - ensure adequate fuel supplies should restocking of fuel supplies be delayed
- ☐ *power* - provide, anchor and test back-up power equipment, such as batteries
- ☐ *power* - size fuel supply tanks for emergency generators; power outages may be longer than expected
- ☐ *communications* - provide, anchor and test back-up equipment, such as portable radios and relay towers
- ☐ *water* - install back-up supplies on-site and anchor tanks
- ☐ *equipment* - anchor all equipment and non-structural items
- ☐ *pipelines* - design on-site utility lines to minimize risk of pipeline breaks
- ☐ *pipelines* - create and isolate shorter segments of pipelines to facilitate repairs by installing additional valves; maintain those pipelines and valves

Location

Examine the location of your facilities relative to exposure to various earthquake hazards described in this report, including:

- ☐ violent shaking
- ☐ liquefaction
- ☐ differential settlement
- ☐ earthquake-induced landsliding

Transportation Providers Checklist

Specific problems in past earthquakes point to particular needs for individual transportation facilities. Because the region relies so much on its transportation network, every provider has as its first concern sustaining operations at its facilities – both for emergency response immediately following an earthquake, and for the flow of commerce during post-earthquake recovery.

Airport Facilities

- ☐ work to minimize the likelihood of closed runways due to pavement buckling from liquefaction or differential settlement
- ☐ sustain utilities (power, communications, water)
- ☐ pay special attention to anchoring equipment in control towers
- ☐ work to maintain access by keeping roads at the facility open
- ☐ evaluate the extent to which general aviation airports could accommodate commercial aircraft in an emergency (perhaps using the Regional Airport Planning Committee - RAPC)

Port Facilities

- ☐ plan for flexibility in providing berthing for commercial ships
- ☐ maintain ship-servicing operations
- ☐ keep ground access open for the movement of goods
- ☐ work with rail operators to ensure rail arteries for movement of people and goods to and from ships, both in pre-planning and post-event recovery
- ☐ anticipate potential problems with liquefaction affecting terminals, quay walls, and on-site underground pipelines

Rail Facilities

- ☐ survey all track segments to identify segments in areas susceptible to ground rupture (faulting) or ground failure (liquefaction or sliding)
- ☐ *electric rail-based transit* - should develop ways to supplement outside power for train operations, such as in BART's tube and tunnel
- ☐ *rail-based transit* - should work with the Metropolitan Transportation Commission and other agencies to expedite funding of seismic strengthening of elevated rail supports
- ☐ *BART* - should coordinate possible use of the transbay tube for connection with bus service should both the Bay Bridge and the remainder of the BART system be out of service
- ☐ *rail freight and Amtrak* - should ensure that the national management understands the specific issues related to seismic safety in California

Transit Facilities

- ☐ pay special attention to ways for employees (both drivers and maintenance workers) to get to work
- ☐ pay special attention to fuel and back-up power needs
- ☐ work with other transit districts and establish mutual aid agreements for bus use
- ☐ anticipate the need to be flexible and change post-earthquake bus routes and schedules; have a means to communicate those changes to customers and among drivers

Utilities Checklist

Utilities will need to use streets which connect to critical facilities and to use (and sometimes disrupt) streets to repair breaks in pipelines. Utilities need to pre-plan for transportation disruptions to minimize service outages and to respond quickly once those outages occur.

General

- ☐ anticipate that repair crews will experience problems gaining access to areas requiring service by establishing key transportation corridors to facilities based, in part, on avoiding problem areas as mapped in this report whenever feasible
- ☐ communicate important messages to the public **before** an event occurs, stressing:
  - (a) install of backup power, water and communication
  - (b) do ***not*** shut off gas pilot lights unless gas is leaking as it could be days before utility personnel relight them
  - (c) do ***not*** call utilities about power outages
  - (d) avoid telephones unless necessary to keep from jamming phone lines
  - (d) remember that crews are working as quickly as possible to restore services
- ☐ maintain mutual aid agreements and communication with other utility companies

Water Supply

- ☐ anticipate areas of pipeline breaks to pre-plan routing of repair vehicles
- ☐ ensure back-up power for wells, pumping facilities and treatment plants
- ☐ use the Water Agency Response Network to request emergency assistance including equipment, supplies, and personnel
- ☐ work for better communication between water wholesalers and retailers regarding service continuities and emergency supplies

Wastewater

- ☐ ensure back-up power for sewage treatment plants not dependent on gravity flow

Power and Natural Gas Facilities

- ☐ ensure reliable emergency communication between repair vehicles and dispatch centers
- ☐ anticipate areas of pipeline breaks to pre-plan routing of repair vehicles

Telecommunications

- ☐ pay special attention to repeater stations, which have tended to be more structurally vulnerable than other links

Emergency Service Providers Checklist

Emergency responders will be using roads to respond to problems, as well as to gain access to key facilities such as police stations, fire stations, and hospitals.

Police and Fire

- ☐ ensure emergency communications facilities are "hardened"
- ☐ have access to adequate fuel for response vehicles, and install emergency generators on the fuel pumps
- ☐ exercise response plans based on realistic scenarios, such as those described in this report

Health Care

- ☐ anticipate problems gaining access to areas with injured people or returning to medical facilities
- ☐ pre-plan the expected quickest and safest routes to arrive at hospitals
- ☐ work with utilities and transportation providers to anticipate transportation bottlenecks and to pre-plan routing
- ☐ maintain mutual aid agreements with other hospitals in order to share resources if and when needed
- ☐ make available better communications between hospitals and response personnel after an event in case responders or patients need to be sent elsewhere

Mass Care (Feeding and Sheltering)

- ☐ ensure that accurate and reliable information on road conditions will be continually available to job headquarters
- ☐ ensure functioning and availability of a reliable communication system between job headquarters and shelters and between job headquarters and supply sources
- ☐ anticipate problems gaining access to supply sources and shelters caused by disruptions in the transportation system and traffic bottlenecks
- ☐ anticipate problems establishing transportation links between supply sources and shelters caused by disruptions in the transportation system and traffic bottlenecks
- ☐ ensure that predesignated direct relief centers and job headquarters are not of a type of construction that is prone to structural problems in earthquakes

Local Government Checklist

Local governments have to balance the potentially conflicting transportation needs of citizens with the needs of transportation providers, utility companies, and emergency services officials.

Transportation and Emergency Planning

- ☐ identify areas that can be used for multi-modal transportation needs such as helipads, docks and connection points
- ☐ plan alternative routes and methods of transportation to areas with large numbers of potential street and freeway closures
- ☐ investigate the possibility of establishing standards and systems for clearly marking "emergency vehicle routes."
  Advantages include the potential to:
  (a) strengthen these routes against disruptions,
  (b) separate emergency traffic from local traffic, and
  (c) ease emergency access.
  Disadvantages include:
  (a) possible problems with public enforcement,
  (b) difficulties in predicting where routes will be needed, and
  (c) development of false expectations about open routes.
- ☐ develop and periodically update a directory of key Bay Area transportation agencies and contacts
- ☐ foster mutual aid agreements with other similar agencies, so that emergency repairs and operations can begin immediately
- ☐ plan innovative methods for route control and enforcement, since the number of detours and closed streets may overwhelm the resources of police and public works departments

Public Works

- ☐ identify staging areas for equipment, supplies, and fuel to support emergency support operations in the first 72 hours
- ☐ develop contingency contracts with local contractors enabling them to begin repairing critical roadways immediately
- ☐ adopt and exercise damage assessment methods
- ☐ explore the possibility of storing temporary (Bailey) bridges to replace critical water crossings

Communication and Public Outreach

- ☐ plan and exercise methods for disseminating public information
- ☐ inform citizens that some roads may not open for several days due to the priority of repairing roads used by emergency vehicles
- ☐ suggest local employers develop emergency telecommuting options for their employees
- ☐ cooperate with Caltrans and key utilities to ensure mutual knowledge of key facilities to improve post-earthquake access
- ☐ implement redundant communications systems
- ☐ improve post-earthquake communications between agencies by designating an agency representative for each EOC

Private Companies and Residents Checklist

Employees will need to use roads to get to work, as well as to gain access to key facilities that need repair. People should use the maps in this report to anticipate transportation disruptions in areas through which they generally travel.

As an Employee or Employer

- ☐ plan alternative routes and methods of transportation
- ☐ work with employers/employees on emergency telecommuting options
- ☐ plan on utilizing mass transit or carpools if telecommuting is not an option
- ☐ plan on not working for up to 72 hours after an earthquake, due to phone and travel restrictions necessary for emergency operations
- ☐ identify staging areas and stockpile emergency supplies and equipment so as to support employees and business concerns for the first 72 hours after an earthquake
- ☐ plan methods for disseminating post-earthquake information to employees and their families

As a Resident

- ☐ plan on being self sufficient for up to three days by storing, at a minimum, the following items:
  - (a) at least one gallon of water per person per day
  - (b) a three-day supply of non-perishable food
  - (c) a three-day supply of personal medication
  - (d) a first aid kit
  - (e) sanitation supplies (toilet paper, garbage bags, bleach, etc.)
  - (f) a battery-operated radio to get information on road conditions and other emergency communications
  - (g) items for people with special needs
- ☐ anticipate having to stay at work for several days should an earthquake happen during work hours, and ensure that your employer has adequate emergency supplies
- ☐ anticipate having to stay at a shelter if staying at or traveling to home or work is not an option
- ☐ determine alternative routes from your home and employer to child care, emergency care facilities, and other key locations
- ☐ follow the authorities' instructions on, for example, travel and phone usage after an earthquake in order to help speed the recovery process

As a Parent

- ☐ work with your school or day care provider to ensure that your children can be taken care of should you or someone you designate not be able to pick them up following an earthquake
- ☐ take the filling out of emergency cards and information seriously; remember that you may not be able to personally pick up your children following a major earthquake

APPENDIX B: DATA ON ROAD CLOSURES FOLLOWING THE LOMA PRIETA AND NORTHRIDGE EARTHQUAKES ...

Overview

As stated in the body of this report in the section on "Street and Freeway Disruptions - Experiences During the Loma Prieta and Northridge Earthquakes," an accurate assessment of these impacts is required in order to understand the effects of future earthquakes on the transportation system. The assessment did not limit itself to freeways and highways, but also included regional thoroughfares and local city streets.

For the purposes of this report, disruptions to the transportation system were measured in terms of traffic closures to streets and freeways. In order to use these data for modeling future street and freeway closures, several types of information were collected for each closure. The table which follows includes separate listings for the Loma Prieta and Northridge events, as well as:
LOCATION DATA

- county
- city
- street
- address range

CLOSURE DATA

- full versus partial
- cause
- passable (public safety closure only) (versus literally being impassable)
- number of days closed

The actual database has separate fields for each closure cause (to allow for multiple closures), the dates the segment was closed and reopened, and various comment fields.

The complete closure database is available from ABAG on diskette as a dbf formatted file (ABAG Publication P97ØØ1EQK).

EARTHQUAKE STREET CLOSURES: LOMA PRIETA

County/City	Street	Address Range	Closure	Hazard	Passable	Days Closed
ALAMEDA COUNTY						
BERKELEY-OAKLAN	I-80 W.B.	GILMAN-ASHBY	Full	Liquefaction	Yes	1
EMERYVILLE	I-80 E.B.	DISTRIBUTION STRE TO POWELL	Partial	Liquefaction	Yes	95
EMERYVILLE	I-80 W.B.	ASHBY-POWELL	Partial	Liquefaction	Yes	1
OAKLAND	16TH STREET	PERALTA-KIRKHAM	Full	Freeway Hazard	No	166
OAKLAND	17TH STREET	PERALTA-KIRKHAM	Full	Freeway Hazard	No	166
OAKLAND	18TH STREET	PERALTA-KIRKHAM	Full	Freeway Hazard	No	166
OAKLAND	20TH ST	SAN PABLO-CASTRO STREET	Partial	Building Damage	Yes	31
OAKLAND	20TH STREET	PERALTA-KIRKHAM STREET	Full	Freeway Hazard	No	166
OAKLAND	24TH STREET	CAMPBELL-PERALTA	Full	Freeway Hazard	No	166
OAKLAND	26TH STREET	WILLOW-CAMPBELL	Full	Freeway Hazard	No	166
OAKLAND	BROADWAY	14TH-15TH STREETS	Partial	Building Damage	Yes	131
OAKLAND	FRANKLIN ST	21ST-BROADWAY	Full	Building Damage	Yes	31
OAKLAND	I-580 W.B.	ON RAMP AT MACARTHUR & SAN PABLO	Full	Traffic Control	Yes	177
OAKLAND	I-80 E.B. (B.BRIDGE)	TREASURE ISLAND-OAKLAND B BRIDGE	Full	Shaking	No	31
OAKLAND	I-80 E.B. PORT OF OAKLN	WEST-GRAND ON RAMP	Full	Shaking Liquefaction	No	126
OAKLAND	I-80 W.B. (B.BRIDGE)	TREASURE ISLAND-OAKLAND B BRIDGE	Full	Shaking	No	31
OAKLAND	I-80 W.B. P. OF OAKLAND	WEST-GRAND ON RAMP	Full	Shaking Liquefaction	No	126
OAKLAND	I-880 N.B. (CYPRESS)	I-80/I-580 JUNCTION-I-980	Full	Shaking	No	3088
OAKLAND	I-880 S.B. (CYPRESS)	I-80/I-580 JUNCTION-I-980	Full	Shaking	No	3088
OAKLAND	I-980 W.B.	11TH STREET ON RAMP	Full	Traffic Control	Yes	3
OAKLAND	I-980 W.B. CONNECTOR	CONNECTOR FROM W.B.24-WB 980	Full	Traffic Control	Yes	4
OAKLAND	I-980 W.B. CONNECTOR S.B.	16TH STREET-SB I-880	Full	Shaking	Yes	3
OAKLAND	I-980 W.B. ON RAMP	17TH STREET ON RAMP	Full	Shaking	Yes	3
OAKLAND	MANDELA PARKWAY	16TH-32ND	Full	Freeway Hazard	No	166
OAKLAND	WEST GRAND AVE	PERALTA-CYPRESS	Full	Freeway Hazard	No	166
CONTRA COSTA COUNTY						
CC COUNTY	I-680 S.B.	MARINA VISTA OFF RAMP'	Full	Shaking	Yes	3
EL SOBRANTE	VALLEY VIEW RD	AT SAN PABLO DAM	Partial	Water Pipe Break	Yes	3
SAN FRANCISCO COUNTY						
SAN FRANCISCO	10TH STREET	MARKET-MISSION	Partial	Other	Yes	1
SAN FRANCISCO	11TH	FOLSOM-HARRISON	Partial	Building Damage	Yes	31

County/City	Street	Address Range	Closure	Hazard	Passable	Days Closed
SAN FRANCISCO	2ND STREET	MISSION-MINNA	Partial	Building Damage	Yes	14
SAN FRANCISCO	5TH STREET	BRANNAN-TOWNSEND	Partial	Building Damage	Yes	1
SAN FRANCISCO	6TH STREET	HOWARD-FOLSOM	Full	Liquefaction Building Damage	Yes	45
SAN FRANCISCO	6TH STREET	BLUXOME-TOWNSEND	Full	Liquefaction Building Damage	Yes	31
SAN FRANCISCO	6TH STREET	AT BRANNAN	Full	Building Damage	Yes	1
SAN FRANCISCO	9TH STREET	MARKET-MISSION	Partial	Building Damage	Yes	1
SAN FRANCISCO	AVILA	MARINA-FRANCISCO	Partial	Building Damage Water Pipe Break	Yes	89
SAN FRANCISCO	BAKER ST	MARINA-FRANCISCO	Partial	Traffic Control	Yes	89
SAN FRANCISCO	BATTERY	BUSH-MARKET	Partial	Traffic Control	Yes	1
SAN FRANCISCO	BAY	GRANT-KEARNY	Partial	Landslide	Yes	1
SAN FRANCISCO	BAY ST	BAKER-FILLMORE	Partial	Building Damage Water Pipe Break	Yes	89
SAN FRANCISCO	BEACH	BAKER-FILLMORE	Partial	Liquefaction Building Damage Water Pipe Break	Yes	89
SAN FRANCISCO	BEALE	MARKET-MISSION	Partial	Traffic Control	Yes	1
SAN FRANCISCO	BLUXOME	6TH-5TH	Full	Liquefaction Building Damage	Yes	30
SAN FRANCISCO	BROADWAY	LARKIN-POWELL	Partial	Other	Yes	45
SAN FRANCISCO	BRODERICK	MARINA-FRANCISCO	Partial	Building Damage	Yes	89
SAN FRANCISCO	BRYANT	9TH-8TH	Partial	Freeway Hazard	Yes	31
SAN FRANCISCO	BUSH STREET	PIERCE-STEINER	Full	Building Damage	Yes	45
SAN FRANCISCO	CALIFORNIA	BATTERY-FRONT	Full	Building Damage	Yes	15
SAN FRANCISCO	CALIFORNIA	MONTGOMERY-SANSOME	Partial	Other	Yes	1
SAN FRANCISCO	CAPRA WAY	SCOTT-MALLORCA	Partial	Building Damage Water Pipe Break	Yes	89
SAN FRANCISCO	CERVANTES	MARINA-FILLMORE	Partial	Building Damage Water Pipe Break	Yes	89
SAN FRANCISCO	DIVISADERO ST	MARINA-FRANCISCO	Partial	Building Damage Water Pipe Break	Yes	89
SAN FRANCISCO	EMBARCADERO	JACKSON-WASHINGTON	Partial	Freeway Hazard	Yes	45
SAN FRANCISCO	EMBARCADERO	BROADWAY-JACKSON	Partial	Freeway Hazard	Yes	45
SAN FRANCISCO	EMBARCADERO	MISSION-HOWARD	Partial	Liquefaction	Yes	342
SAN FRANCISCO	EMBARCADERO	MARKET-MISSION	Partial	Liquefaction	Yes	342
SAN FRANCISCO	EMBARCADERO	CLAY-MARKET	Partial	Liquefaction	Yes	45
SAN FRANCISCO	FOLSOM	11TH-JUNIPER	Partial	Building Damage	Yes	31
SAN FRANCISCO	FRANCISCO	BAKER-FILLMORE	Partial	Building Damage Water Pipe Break	Yes	89

County/City	Street	Address Range	Closure	Hazard	Passable	Days Closed
SAN FRANCISCO	FREMONT	MARKET-MISSION	Partial	Building Damage	Yes	15
SAN FRANCISCO	FRONT STREET	CALIFORNIA-PINE	Full	Building Damage	Yes	15
SAN FRANCISCO	FRONT STREET	SACRAMENTO-CALIFORNIA	Full	Building Damage	Yes	45
SAN FRANCISCO	GEARY	WEBSTER-LAGUNA	Partial	Water Pipe Break	Yes	8
SAN FRANCISCO	GOUGH	GROVE-HAYES	Partial	Freeway Hazard	Yes	42
SAN FRANCISCO	GRANT	BEACH-NORTHPOINT	Full	Building Damage	Yes	45
SAN FRANCISCO	HAYES	OCTAVIA-GOUGH	Partial	Freeway Hazard	Yes	39
SAN FRANCISCO	HOWARD	3RD-HAWTHORNE	Partial	Building Damage	Yes	15
SAN FRANCISCO	I-280 N.B.	101-6TH STREET SO FRWY VIADUCT	Full	Shaking	Yes	107
SAN FRANCISCO	I-280 S.B.	S.R. 101-6TH STREET SO FRWY VIADUC	Full	Shaking	Yes	107
SAN FRANCISCO	I-480 N.B.	I-80 TO BROADWAY CLAY	Full	Shaking	Yes	805
SAN FRANCISCO	I-480 S.B.	I-80 TO BROADWAY CLAY	Full	Shaking	Yes	805
SAN FRANCISCO	I-80 E.B.	8TH STREET ON RAMP	Full	Traffic Control	Yes	164
SAN FRANCISCO	I-80 E.B.	5TH STREET ON RAMP	Full	Traffic Control	Yes	31
SAN FRANCISCO	I-80 E.B.	4TH STREET TO BAY BRIDGE	Full	Shaking	Yes	31
SAN FRANCISCO	IVY	GOUGH-OCTAVIA	Partial	Freeway Hazard	Yes	39
SAN FRANCISCO	JEFFERSON ST.	BAKER-FILLMORE	Partial	Building Damage Water Pipe Break	Yes	89
SAN FRANCISCO	JESSIE	NEW MONTGOMERY-ANNIE	Full	Building Damage	Yes	45
SAN FRANCISCO	MALLORCA WAY	CERVANTES-TOLEDO	Partial	Building Damage Water Pipe Break	Yes	89
SAN FRANCISCO	MARINA BLVD	BAKER-FILLMORE	Partial	Liquefaction Water Pipe Break	Yes	89
SAN FRANCISCO	MARKET	1ST-FREMONT	Full	Traffic Control	Yes	1
SAN FRANCISCO	MARKET	2ND-1ST	Full	Traffic Control	Yes	1
SAN FRANCISCO	MARKET	3RD-NEW MONTGOMERY	Full	Traffic Control	Yes	1
SAN FRANCISCO	MARKET	4TH-3RD	Full	Traffic Control	Yes	1
SAN FRANCISCO	MARKET	FREMONT-BEALE	Full	Traffic Control	Yes	1
SAN FRANCISCO	MARKET	NEW MONTGOMERY-2ND	Full	Traffic Control	Yes	1
SAN FRANCISCO	MINNA	NEW MONTGOMERY-2ND ST.	Full	Building Damage	Yes	30
SAN FRANCISCO	MISSION	STEUART-EMBARCADERO	Partial	Freeway Hazard	Yes	45
SAN FRANCISCO	MISSION	NEW MONTGOMERY-2ND STREET	Partial	Building Damage	Yes	15
SAN FRANCISCO	NATOMA	NEW MONTGOMERY-2ND	Full	Building Damage	Yes	15
SAN FRANCISCO	NATOMA	5TH-6TH	Partial	Liquefaction Building Damage	Yes	16
SAN FRANCISCO	PIERCE ST	MARINA-FRANCISCO	Partial	Building Damage	Yes	89
SAN FRANCISCO	POINT ST	BAKER-FILLMORE	Partial	Water Pipe Break Traffic Control	Yes	89
SAN FRANCISCO	PRADO ST	SCOTT-CERVANTES	Partial	Building Damage Water Pipe Break	Yes	89

County/City	Street	Address Range	Closure	Hazard	Passable	Days Closed
SAN FRANCISCO	RICO WAY	PRADO- CASA RETIRO WAY	Partial	Water Pipe Break Traffic Control	Yes	89
SAN FRANCISCO	RICO WAY	PRADO-CASA RETIRO	Partial	Water Pipe Break Traffic Control	Yes	89
SAN FRANCISCO	SCOTT ST	MARINA-FRANCISCO	Partial	Building Damage	Yes	89
SAN FRANCISCO	STATE ROUTE 1 N.B.	LAKE STREET-MACARTHUR TUNNEL	Partial	Landslide	Yes	0
SAN FRANCISCO	STATE ROUTE 101 N.B.	FELL ST-GOLDEN GATE	Full	Shaking	Yes	155
SAN FRANCISCO	STATE ROUTE 101 S.B.	TURK ST-OAK ST	Full	Shaking	Yes	155
SAN MATEO COUNTY						
DALY CITY	I-280 N.B. ON RAMP	FROM DALY CITY	Full	Traffic Control	Yes	1
SAN MATEO	I-380 E.B.	I-280-S.R. 101	Full	Shaking	Yes	0
SAN MATEO	I-380 W.B.	I-280-S.R. 101	Full	Shaking	Yes	0
SAN MATEO	STATE ROUTE 101 N.B.	NB101-WB92	Full	Shaking	Yes	15
SAN MATEO	STATE ROUTE 92 E.B.	FOSTER CITY BLVD-CLAWITER RD	Full	Shaking	Yes	1
SAN MATEO	STATE ROUTE 92 W.B.	FOSTER CITY BLVD-CLAWITER RD	Full	Shaking	Yes	1
SANTA CLARA COUNTY						
COUNTY	STATE ROUTE 152 E.B.	CARLTON RD- SANTA TERESA BLVD	Full	Landslide	Yes	0
COUNTY	STATE ROUTE 152 W.B.	CARLTON RD- SANTA TERESA BLVD	Full	Landslide	Yes	0
COUNTY	STATE ROUTE 35	S.R. 9- S.R. 17	Full	Landslide	No	2
LOS GATOS	LOS GATOS BLVD	S. GATEWAY	Partial	Water Pipe Break	Yes	30
LOS GATOS	N. SANTA CRUZ A	MAIN-ELM	Full	Building Damage	Yes	30
LOS GATOS	RIGHT STATION ROAD	LOCAL BRIDGE	Full	Shaking	Yes	196
SAN JOSE	I-280 E.B.	MORA DR. OVERCROSSING	Full	Shaking	Yes	2
SAN JOSE	I-280 W.B.	MORA DR. OVERCROSSING	Full	Shaking	Yes	2
SCL COUNTY	STATE ROUTE 101 N.B.	PAJARO RIVER BRIDGE	Partial	Shaking	Yes	1
SANTA CRUZ COUNTY						
COUNTY	BEAN CREEK RD	SCOTTS VALEY DR.- GLENWOO	Full	Landslide	No	55
COUNTY	BEAR CREEK RD	HWY 17-	Partial	Landslide	Yes	15
COUNTY	BROWNS VALLEY R		Partial	Landslide	Yes	45
COUNTY	BUZZARD LAGOON	3 MLS FROM EUREKA CANYON	Partial	Landslide	Yes	52
COUNTY	EUREKA CANYON R		Partial	Landslide	No	52
COUNTY	GREEN VALLEY RD	1700 BLOCK	Partial	Landslide	No	52
COUNTY	OLD SAN JOSE RD	AT LAUREL GLEN RD	Partial	Landslide	No	56
COUNTY	RODEO GULCH RD.	SOQUEL- BRANCIFORTE DR.	Partial	Landslide	No	52
COUNTY	STATE ROUTE 1 S.B.	GRANITE RD-UNIVERSITY OF CALIFORNIA	Partial	Landslide	Yes	1

County/City	Street	Address Range	Closure	Hazard	Passable	Days Closed
COUNTY	STATE ROUTE 129 E.B.	SAN JUAN RD-HWY 101	Full	Landslide	No	11
COUNTY	STATE ROUTE 129 W.B.	SAN JUAN RD- S.R. 101	Full	Landslide	No	11
COUNTY	STATE ROUTE 236	S. OF BIG BASIN STATE PARK MILE 7.3	Full	Landslide	No	386
COUNTY	STATE ROUTE 25 N.B.	S.R. 101-SAN BENITO COUNTY LINE	Full	Landslide	No	2
COUNTY	STATE ROUTE 25 S.B.	S.R. 101-SAN BENITO COUNTY LINE	Full	Landslide	No	2
COUNTY	STATE ROUTE 9 N.B.	S.R. 1- S.R. 17	Full	Landslide	No	2
COUNTY	STATE ROUTE 9 S.B.	S.R. 1- S.R. 17	Full	Landslide	No	2
SANTA CRUZ	CHURCH	CEDAR-PACIFIC	Full	Building Damage	Yes	56
SANTA CRUZ	COOPER ST	PACIFIC-FRONT	Full	Building Damage	Yes	56
SANTA CRUZ	LOCUST ST	PACIFIC-CEDAR	Full	Building Damage	Yes	56
SANTA CRUZ	MURRAY ST	LOCAL BRIDGE	Full	Shaking	No	227
SANTA CRUZ	PACIFIC AVE	WALNUT-FRONT	Full	Building Damage	Yes	56
SANTA CRUZ	RIVERSIDE AVE	LOCAL BRIDGE	Full	Shaking	No	500
SANTA CRUZ	SOQUEL AVE	PACIFIC-FRONT	Partial	Building Damage	Yes	56
SCR COUNTY	STATE ROUTE 1 N.B.	S.R. 152- S.R. 129 STRUVE SL	Full	Shaking Liquefaction	No	100
SCR COUNTY	STATE ROUTE 1 S.B.	S.R. 152-S.R. 129 STRUVE SL	Full	Shaking Liquefaction	No	100
WATSONVILLE	MAIN ST	LOCAL BRIDGE AT PAJARO RIVER	Partial	Shaking Liquefaction	Yes	2904

SANTA CRUZ-SANTA CLARA COUNTY

County/City	Street	Address Range	Closure	Hazard	Passable	Days Closed
COUNTY	STATE ROUTE 17 N.B.	L.G. S.R. 9-SCOTTS VALLEY(G CREEK R	Full	Landslide	No	33
COUNTY	STATE ROUTE 17 S.B.	L.G. S.R.9-SCOTTS VALLEY(G CREEK RD	Full	Landslide	No	33

EARTHQUAKE STREET CLOSURES: NORTHRIDGE

County/City	Street	Address Range	Closure	Hazard	Passable	Days Closed
LOS ANGELES COUNTY						
LOS ANGELES	1100 BELAGIO PL		Partial	Landslide	No	1
LOS ANGELES	6TH STREET	COMMONEALTH AVE-HOOVER ST	Full	Building Damage	Yes	6
LOS ANGELES	ADAMS BL	ADAMS BL AND ALSACE AVE	Partial	Building Damage	Yes	4
LOS ANGELES	ALSACE AVE	NORTH OF ADAMS BL	Partial	Building Damage	Yes	4
LOS ANGELES	ANGELO DR	MOSSY ROCK CIRCLE-BAYWOOD CT	Full	Natural Gas Release	Yes	4
LOS ANGELES	BALBOA BL	HWY 118-MIDWOOD	Full	Natural Gas Release Water Pipe Break	No	62
LOS ANGELES	BARHAM BL	FOREST LAWN DR-OLIVE DR	Full	Shaking	Yes	4
LOS ANGELES	BARRINGTON AVE	AT OLYMPIC BL	Full	Building Damage	Yes	2
LOS ANGELES	BARRINGTON AVE	MISSISSIPPI ST-PICO BL	Full	Building Damage	Yes	15
LOS ANGELES	BELAGIO PLACE	1100 BLOCK	Full	Landslide	Yes	5
LOS ANGELES	BENEDICT CANYON	2800 BENEDICT CANYON	Partial	Landslide	No	1
LOS ANGELES	BEVERLY GLEN BL	S. OF MULHOLLAND DR	Full	Landslide	Yes	5
LOS ANGELES	BROADWAY	AT 7TH STREET	Partial	Water Pipe Break	Yes	1
LOS ANGELES	BROWN'S CANYON ROAD	1 MILE N. OF FRWY 118	Partial	Landslide	Yes	2
LOS ANGELES	BURBANK BL	E. OF RESEDA BL	Partial	Other	Yes	14
LOS ANGELES	CHALON RD	11080 CHALON-STRADELLA	Partial	Landslide	No	1
LOS ANGELES	CHASE ST	ENFIELDS AVE-NEWCASTLE AVE	Full	Water Pipe Break	Yes	4
LOS ANGELES	CHATAQUA	100 BLOCK	Partial	Landslide	No	1
LOS ANGELES	CHAUTAUQUA	VANCE ST-PACIFIC COAST HWY	Full	Landslide	Yes	5
LOS ANGELES	COLDWATER CANYON AVE	VENTURA BL-MULHOLLAND DR.	Full	Landslide	Yes	1
LOS ANGELES	COLE AVE	LEXINGTON AVE-SANTA MONICA BL	Full	Traffic Control	Yes	38
LOS ANGELES	COLISEUM STREET	5730 COLISEUM STREET	Partial	Liquefaction	Yes	4
LOS ANGELES	DE SOTO AVENUE	ROSCOE AVE-SATICOY ST	Full	Other	Yes	1
LOS ANGELES	ELLENITA AVE	ROSITA AVE-SLEEPY HOLLOW LN	Full	Water Pipe Break	Yes	7
LOS ANGELES	ELUSIVE DRIVE	8300 BLOCK	Full	Landslide	No	1
LOS ANGELES	ENTRADA DR	SHORT ST-PACIFIC COAST HWY	Full	Building Damage	No	8
LOS ANGELES	ESCALON DR	AT 16811	Partial	Liquefaction	Yes	4
LOS ANGELES	FAIRFAX AVE	UNDERPASS AT I-10 FRWY	Full	Freeway Hazard	No	15
LOS ANGELES	FOOTHILL BL	YARNELL ST-SIERRA HWY	Partial	Traffic Control	Yes	4
LOS ANGELES	FRANKLIN AVE	ST GEORGE ST-MYRA AVE	Full	Shaking	Yes	1
LOS ANGELES	FRIAR ST	VAN NUYS BL-ALLEY E/O VAN NUYS	Full	Building Damage	Yes	12
LOS ANGELES	GAYLEY AVE	641-629 GAYLEY AVE	Partial	Water Pipe Break	No	1
LOS ANGELES	GEORGE BURNS RD	ALDEN DR-3RD STREET	Partial	Building Damage	Yes	14
LOS ANGELES	GOTHIC AVE	AT FRWY 118 WOODLEY-HAYVENHURST	Full	Freeway Hazard	No	113
LOS ANGELES	GRANDE VISTA AVE	AT WASHINGTON BL	Partial	Shaking	Yes	7
LOS ANGELES	HAYVENHURST AVE	STAGG ST-SATICOY ST	Full	Haz. Mat. Release	Yes	4

County/City	Street	Address Range	Closure	Hazard	Passable	Days Closed
LOS ANGELES	HILLCREST DR	AT 3531 HILLCREST DR	Partial	Liquefaction	Yes	4
LOS ANGELES	HILTS AVE	AT 1027	Partial	Water Pipe Break	Yes	7
LOS ANGELES	I-10 E.B.	LA CIENEGA TO WASHINGTON	Full	Shaking	No	84
LOS ANGELES	I-10 W.B.	LA CIENEGA TO WASHINGTON	Full	Shaking	No	84
LOS ANGELES	I-10 W.B. CONNECTOR	TO S.B. 405	Full	Shaking	Yes	2
LOS ANGELES	I-210 E.B. CONNECTOR	TO W.B. 118	Full	Traffic Control	Yes	22
LOS ANGELES	I-210 W.B.	CONNECTORS TO 118 W.B.	Full	Shaking	Yes	29
LOS ANGELES	I-210 W.B.	CONNECTORS TO I-5 N.B.	Full	Shaking	Yes	29
LOS ANGELES	I-210 W.B. CONNECTOR	TO S.B. I-5	Full	Shaking	Yes	3
LOS ANGELES	I-405 N.B.	AT DEVONSHIRE-I-5	Full	Shaking	No	10
LOS ANGELES	I-405 N.B. CONNECTOR	TO 118 E.B.	Full	Traffic Control	Yes	116
LOS ANGELES	I-405 N.B. CONNECTOR	TO 118 W.B.	Full	Shaking	Yes	22
LOS ANGELES	I-405 S.B. CONNECTOR	TO RTE 118	Full	Shaking	Yes	22
LOS ANGELES	I-5 S.B.	LYONS AVE- I-210	Full	Shaking	No	165
LOS ANGELES	I-5 S.B. CONNECTOR	TO E.B. 118,	Full	Shaking	No	22
LOS ANGELES	I-5 S.B. CONNECTOR	TO W.B. 118	Full	Shaking	No	22
LOS ANGELES	I-5 N.B.	LYONS AVE- I-210	Full	Shaking	No	121
LOS ANGELES	I-5 N.B.	AT MAGIC MOUNTAIN PARKWAY	Partial	Shaking	No	111
LOS ANGELES	I-5 N.B. CONNECTOR	CONNECTORS TO E.B. I-210	Full	Shaking	No	22
LOS ANGELES	I-5 N.B. CONNECTOR	TO E.B. 118	Full	Shaking	No	22
LOS ANGELES	I-5 S.B.	NORTH OF RTE 138	Partial	Traffic Control	Yes	5
LOS ANGELES	I-5 W.B. CONNECTOR	TO W.B.118	Full	Traffic Control	Yes	22
LOS ANGELES	JEFFERSON BL	S. OF HOLDREDGE AVE	Partial	Water Pipe Break	Yes	10
LOS ANGELES	JUANITA AVE	OAKWOOD AVE-BEVERLY BL	Full	Water Pipe Break	Yes	5
LOS ANGELES	KNOB HILL DR	AT BEVERLY GLEN BL	Full	Water Pipe Break	Yes	5
LOS ANGELES	KNOBHILL DR	AT BEVERLY GLENN BL	Full	Water Pipe Break	Yes	6
LOS ANGELES	LA CIENEGA BLVD	UNDERPASS AT I-10 FRWY	Full	Freeway Hazard	No	114
LOS ANGELES	LAKE MANOR RD	AT VALLEY CIRCLE CL	Full	Landslide	Yes	5
LOS ANGELES	LEDGE AVE	HUSTON ST-CAMARILLO ST	Partial	Water Pipe Break	Yes	1
LOS ANGELES	LINDLEY AVE	SHERMAN WY-GAULT ST	Full	Building Damage	Yes	8
LOS ANGELES	MANNIX DR	KIRKWOOD DR-DE E/O KIRKWOOD DR	Full	Landslide	Yes	22
LOS ANGELES	MARTIN LUTHER KING JR	AT RODEO RD	Partial	Liquefaction	Yes	1
LOS ANGELES	MARTIN LUTHER KING JR	AT BUCKINGHAM RD	Partial	Water Pipe Break	Yes	10
LOS ANGELES	MOORPARK STREET	WOODMAN AVE-FULTON AVE	Full	Other	Yes	1
LOS ANGELES	MOUNT LEE DR.		Partial	Landslide	No	1
LOS ANGELES	MULHOLLAND DR	BEVERLY GLEN-NICADA DR	Full	Water Pipe Break	Yes	8
LOS ANGELES	MULHOLLAND DR	AT I-405	Full	Freeway Hazard	Yes	4
LOS ANGELES	MULHOLLAND DR	AT MULHOLLAND PLACE	Full	Landslide	Yes	5
LOS ANGELES	MULHOLLAND DR	SKIRBALL CENTER-CALNEVA DR	Full	Shaking	Yes	5
LOS ANGELES	MULHOLLAND DR	DIXIE CANYON AVE-BEVERLY GLEN BL	Partial	Landslide	Yes	3
LOS ANGELES	MULHOLLAND DR.	WRIGHTWOOD DR.-ROSCOMARS RD	Partial	Landslide	No	1

County/City	Street	Address Range	Closure	Hazard	Passable	Days Closed
LOS ANGELES	NORDHOFF STREET	BRIDGE WEST OF TAMPA AVE	Full	Shaking	No	135
LOS ANGELES	OAKFIELD DR	BEVERLY GLEN BL-MILBROOK DR	Full	Liquefaction	Yes	10
LOS ANGELES	OCCIDENTAL BL	BEVERLY BL- 2ND ST	Full	Traffic Control	Yes	4
LOS ANGELES	OLYMPIC BL	BOYLE AVE-SANTA FE STREET	Full	Freeway Hazard	Yes	1
LOS ANGELES	OLYMPIC BL	BUNDY ST-BARRY ST	Full	Building Damage	Yes	9
LOS ANGELES	OLYMPIC BLVD	WEST OF FEDERAL AVENUE	Full	Other	Yes	1
LOS ANGELES	PARTHENIA ST	AT 17360 PARTHENIA	Partial	Liquefaction	Yes	10
LOS ANGELES	PARTHENIA ST	AT 17599 PARTHENIA ST	Partial	Landslide	Yes	10
LOS ANGELES	PAXTON STREET	SHARP AVE- ARLETA AVE	Full	Freeway Hazard	Yes	1
LOS ANGELES	RESEDA	SATICOY ST-ROSCOE BL	Partial	Natural Gas Release	Yes	7
LOS ANGELES	RESEDA BL	SUPERIOR ST-PLUMMER ST	Full	Building Damage	Yes	4
LOS ANGELES	RINALDI	WEST OF I-405	Full	Water Pipe Break	Yes	3
LOS ANGELES	RINALDI STREET	BALBOA BLVD-HAVENHURST AV	Full	Natural Gas Release Water Pipe Break	Yes	1
LOS ANGELES	RINALDI STREET	UNDERPASS AT I-405 FRWY	Full	Freeway Hazard	Yes	3
LOS ANGELES	RINALDI STREET	E OF RESEDA BL	Partial	Freeway Hazard	Yes	1
LOS ANGELES	RINALDI STREET	EAST OF BALBOA BL TO BALBOA	Partial	Liquefaction	Yes	4
LOS ANGELES	RODEO RD	M.L.KING JR. BLVD-EASTERLY FARMDALE	Full	Water Pipe Break	Yes	14
LOS ANGELES	RODEO RD	AT JEFFERSON BL	Partial	Liquefaction	Yes	16
LOS ANGELES	RUFFNER AVE	AT FRWY 118	Partial	Traffic Control	Yes	10
LOS ANGELES	RUFNER AVE	AT HWY 118	Partial	Traffic Control	Yes	2
LOS ANGELES	SAN FERNANDO MISSION BLVD	UNDERPASS AT 118 FRWY	Full	Freeway Hazard	Yes	116
LOS ANGELES	SAN FERNANDO RD	MONTAGUE ST-BRANFORD ST	Full	Shaking	Yes	2
LOS ANGELES	SAN FERNANDO RD	ROXFORD ST-I-5	Full	Liquefaction	Yes	16
LOS ANGELES	SAN FERNANDO RD	BRANFORD ST-SHELDON ST	Full	Liquefaction	Yes	1
LOS ANGELES	SATICOY ST	HAYVENHURST AVE-BALBOA BL	Full	Other	Yes	4
LOS ANGELES	SEPULVEDA BL	AT SEPULVEDA TUNNEL	Partial	Landslide	Yes	1
LOS ANGELES	SEPULVEDA BL	MAGNOLIA BL-101 FWY	Full	Other	Yes	1
LOS ANGELES	SHADOW ISLAND DR	9768 SHADOW ISLAND DR	Partial	Water Pipe Break	Yes	10
LOS ANGELES	SHERMAN WAY	AT WOODLEY AVE	Partial	Other	Yes	1
LOS ANGELES	SHIRLEY AVE	PLUMMER ST - NORDHOFF STREET	Full	Building Damage	Yes	7
LOS ANGELES	STAGG ST	HAYVENHURST AVE-BALBOA BL	Full	Other	Yes	4
LOS ANGELES	STATE ROUTE 1 N.B.	MCCLURE TUNNEL-TEMESCAL C	Full	Landslide	No	7
LOS ANGELES	STATE ROUTE 1 S.B.	RTE 10 MCCLURE TUNNEL-TEMESCAL CANY	Full	Landslide	No	7
LOS ANGELES	STATE ROUTE 101 N.B.	CONNECTORS TO S.R. 170	Partial	Shaking	Yes	7
LOS ANGELES	STATE ROUTE 118 E.B.	AT TAMPA-BALBOA	Full	Shaking	No	116
LOS ANGELES	STATE ROUTE 118 E.B.	BALBOA BL- I-405	Full	Shaking	No	116
LOS ANGELES	STATE ROUTE 118 W.B.	I-210 TO I-405	Full	Shaking	No	29
LOS ANGELES	STATE ROUTE 118 W.B.	I-405-RESEDA	Full	Shaking	No	116
LOS ANGELES	STATE ROUTE 14 N.B.	I-5 -SAN FERNANDO RD	Full	Shaking	No	172
LOS ANGELES	STATE ROUTE 14 S.B.	AT PLACERITA CANYON	Full	Shaking	No	172

County/City	Street	Address Range	Closure	Hazard	Passable	Days Closed
LOS ANGELES	SUNSET BL	BRONSON AVE-GOWER ST	Full	Building Damage	Yes	4
LOS ANGELES	SYCAMORE AVE	2923 SYCAMORE AT EXPOSITION BL	Partial	Water Pipe Break	Yes	1
LOS ANGELES	TAMPA AVE	CHASE ST-NORDHOFF ST	Full	Other	No	14
LOS ANGELES	TERRA BELLA STREET	SAN FERNANDO BLVD-TELFAIR	Full	Other	Yes	1
LOS ANGELES	TUJUNGA AVE	RIVERSIDE DR-MOORPARK ST	Full	Shaking	Yes	1
LOS ANGELES	TYRONE AVE	SYLVAN ST- DELANO ST	Full	Traffic Control	Yes	9
LOS ANGELES	VAN NESS AVE	HOLLYWOOD BL-SUNSET BL	Full	Building Damage	Yes	1
LOS ANGELES	VANALDAN AVE	AT PLUMMAR ST	Partial	Natural Gas Release	Yes	1
LOS ANGELES	VANALDEN AVE	AT PLUMMER ST	Full	Natural Gas Release	Yes	5
LOS ANGELES	VENICE BLVD	UNDERPASS AT I-10 FRWY	Full	Freeway Hazard	No	114
LOS ANGELES	VENTURA BLVD	HAZELTINE AVE-E HAZELTINE	Full	Other	Yes	1
LOS ANGELES	VENTURA BLVD	LAUREL CANYON BLVD-COLFAX AVE	Full	Other	Yes	1
LOS ANGELES	VERNON AVE	WESTERN AVE-CRENSHAW BL	Full	Haz. Mat. Release	Yes	1
LOS ANGELES	VIEWSITE DR	SUNSET PLAZA DR-DEAD END S.SUNSET P	Full	Landslide	Yes	28
LOS ANGELES	VINEYARD AVE	AT 3111 VINEYARD	Partial	Landslide	Yes	4
LOS ANGELES	WASHINGTON BLVD	UNDERPASS AT I-10 FRWY	Full	Freeway Hazard	No	9
LOS ANGELES	WESTERN AVE	OVERPASS OVER HOLLYWOOD FRWY	Full	Freeway Hazard	Yes	1
LOS ANGELES	WHITE OAK ST	AT VANOWEN ST	Full	Natural Gas Release	Yes	1
LOS ANGELES	WHITSETT AVE	SATICOYST-SATICOY ST	Full	Shaking	Yes	22
LOS ANGELES	WILBUR AVE	HATTERAS ST-PHILIPRIM ST	Full	Other	Yes	6
LOS ANGELES	WILLIS AVE	CAMARILLO ST-VENTURA BL	Full	Building Damage	Yes	35
LOS ANGELES	WOLFSKILL ST	SAN FERNANDO RD-LAUREL CANYON BL	Full	Haz. Mat. Release	Yes	14
LOS ANGELES	ZELZAH AVE	AT HWY 118	Full	Freeway Hazard	No	116

APPENDIX C:
SHAKING AMPLIFICATION, LANDSLIDE, AND LIQUEFACTION SUSCEPTIBILITY DATA FOR THE GEOLOGIC UNITS IN THE SAN FRANCISCO BAY AREA

Overview

The 277 separate geologic units which appear in the San Francisco Bay Area have different susceptibilities for amplifying ground shaking, liquefaction, and earthquake-induced landsliding. Although the geologic units and their shaking amplification properties are listed in Appendix B of ***On Shaky Ground*** (Perkins and Boatwright, 1995), they are repeated in this document for ease in comparison with the other two susceptibility values that have not been published by ABAG for all nine Bay Area counties.

Shaking Amplification Susceptibility

The average shaking amplification for the geologic units in the San Francisco Bay Area are based on the properties of the materials contained in those units. This amplification is expressed as predicted intensity increments from Table 43 and are averaged for each geologic unit listed in Table 44 based on those materials. These intensity increments (δI or fractional changes in intensity) are added to (or subtracted from) intensities calculated from the distance/directivity relationship described in Appendix A of ***On Shaky Ground*** (Perkins and Boatwright, 1995) to generate the intensity map values. The list of seismic units which are present in Table 44 is modified and expanded from Fumal (1978) based on personal communications with T. Fumal and J. Gibbs (1978 to 1983) and data on Merritt sand in Borcherdt and Glassmoyer (1992).

Landslide Susceptibility

The method for assigning the landslide susceptibility value to the 277 geologic units in Table 44 is based on the technique and values described by Weiczorek and others (1985) for San Mateo County as:
A - crystalline rocks and well-cemented sandstones
B - unconsolidated and weakly-cemented sandstones
C - shales and clays
The assignments of units in San Mateo County is identical to those published, with the exception of the sandstone layers in the Franciscan Assemblage. These were originally grouped in category A by Weiczorek and others (1985) and reassigned to category C by G. Weiczorek when examining a similar unit in the east Bay (oral communication, 1985). Additional guidance on the assignment of individual geologic materials outside of San Mateo County to these three categories was obtained from oral communications with G. Weiczorek (1983-1985) and with D. Keefer (April 1997). The data which was used to assign the ground failure susceptibility values is similar to those published in the early 1980s by ABAG (in, for example, Perkins, 1982). These values need to be updated

TABLE 43-- SEISMICALLY DISTINCT UNITS AND PREDICTED INTENSITY INCREMENTS
[modified from Borcherdt, Gibbs and Fumal (1978) based on additional shear wave velocity (v) measurements in Borcherdt and Glassmoyer (1992) and the amplification formula in Borcherdt (1994) of $F_v = (1050\ \mathrm{m/s}/v)^{0.65}$. The formula $\delta I = 0.19 + 2.97 \log (F_v)$ from Borcherdt and others (1975) was used to convert amplification to intensity increments.]

Seismic Unit for Sediments	Material Properties			Predicted Intensity Increment
I	Clay and silty clay, very soft to soft			2.4
II	Clay and silty clay, medium to hard			1.8
III	Sand, loose to dense			1.6
IV	Sandy clay-silt loam, interbedded coarse and fine sediment			1.4
V	Sand, dense to very dense			1.1
VI	Gravel			0.7
Seismic Unit for Bedrock	**Rock Type**	**Hardness**	**Fracture Spacing**	**Predicted Intensity Increment**
I	Sandstone	Firm to soft	Moderate and wider	1.0
II	Igneous rocks, Sedimentary rocks	Hard to soft	Close to very close	0.7
III	Igneous rocks, Sandstone, Shale	Hard to firm	Close	0.5
IV	Igneous rocks, Sandstone	Hard to firm	Close to moderate	0.3
V	Sandstone, Conglomerate	Firm to hard	Moderate and wider	0.2
VI	Sandstone	Hard to quite firm	Moderate and wider	0
VII	Igneous rocks	Hard	Close to moderate	-0.2

based on more recent geologic mapping. ABAG is currently seeking funds to update these values and the associated maps.

Liquefaction Susceptibility

The process of mapping liquefaction susceptibility is based on the technique described by Perkins (1979) and Youd and Perkins (1987). The susceptibility units are similar to those described in these reports. The liquefaction mapping techniques used for this project are in the process of being updated and will be available in the Spring of 1998.

TABLE 44 -- OCCURRENCE OF AND AVERAGE PREDICTED INTENSITY INCREMENTS FOR THE GEOLOGIC UNITS IN THE SAN FRANCISCO BAY AREA

The strategraphic nomenclature and unit age assignments used in this table may not necessarily conform to current usage by the U.S. Geological Survey.]

Map Symbol(s)	Geologic Unit	Source Map	Seismic Units Present	Average Predicted Shaking Intensity Increment	Landslide Susceptibility	Liquefaction Susceptibility
Quaternary Units						
1. Qu	Undivided Quaternary alluvium (due to occurrence in urban areas)	Flat	II, III, IV, V, VI	1.3	C	Moderate
2. Qhaf (purple); Qaf	Artificial fill	Flat; CE; SM	II, III, V	1.5	C	Moderate
3. Qhsc; Qal	Holocene stream channel deposits	Flat; SM	III, V	1.4	C	High
4. Qhac; Qyf	Holocene coarse-grained alluvium; fan and basin deposits	Flat; SM	V	1.1	B	Moderate
5. Qham; Qyfo	Holocene medium-grained alluvium; fan and plain deposits	Flat; SM	III	1.6	C	Moderate
6. Qhaf; Qb	Holocene fine-grained alluvium; fan and plain (basin) deposits	Flat; SM	II	1.8	C	Moderate
7. Qhafs	Holocene fine-grained alluvium; fan and plain (basin) deposits--salt-affected	Flat	II	1.8	C	Moderate
8. Qhbm; Qm	Holocene Bay mud	Flat; SM	I	2.4	C	High
9. Qcl	Holocene colluvium; slope wash and ravine fill	SM; data gaps	III, V	1.4	C	Very Low
10. Qhs; Qs	Holocene beach and windblown sand	Flat; SM	III, V	1.4	B	High
11. Qpa	Pleistocene alluvium	Flat	V, VI	0.9	C	Low
12. Qps	Pleistocene sand; Merritt sand	Flat	II	1.8	C	Moderate
13. Qpea	Early Pleistocene alluvium	Flat	V, VI	0.9	C	Low
14. Qof	Pleistocene coarse-grained alluvium; fan deposits	SM	V, VI	0.9	B	Low
15. Qob	Pleistocene fine-grained alluvium; basin deposits	SM	II, IV	1.6	C	Low
16. Qpmt; Qmt	Pleistocene marine terrace deposits	Flat; SM	V	1.1	B	Low
17. Qm	Quaternary Montezuma Formation	NE	V	1.1	B	Very Low
18. Qr	Quaternary tuff and gravel from rhyolite	NC; NE, CMm	V, VI	0.9	B	Very Low
19. Qg	Quaternary gravel, poorly bedded	NC	V, VI	0.9	B	Very Low
20. Qg	Quaternary stream gravel and sand	EBay; SWSC	III, V	1.4	C	Very Low
21. Qr	Quaternary rhyolite of the Clear Lake area	NW; adj. area on NC	III, VII	0.2	A	Very Low
22. Qclt	Quaternary Clear Lake area tuff	NW; NC	I, II	0.8	B	Very Low
23. Qob	Quaternary olivine basalt of Clear Lake area	NC	II, VII	0.2	A	Very Low
24. Qmi	Quaternary Millerton Formation	CMm	III, VI	1.2	C	Very Low
25. Qpmc; Qc	Quaternary Colma Formation	Flat; CMm; SSF; NSF	V	1.1	B	Moderate
26. Qlv	Quaternary boulder gravels of volcanic debris	EBay	VI	0.7	B	Moderate
Quaternary/Tertiary Units						
27. QTs; Qsc	Santa Clara Formation	EBay; SWSC; SM; NWSC	III, IV, V, VI, V, VII	0.8	C	Very Low
28. Qsb	Santa Clara Formation--gravel with basalt detritus	EBay	V, VI	0.9	B	Very Low
29. Qsp	Santa Clara Formation--conglomerate or breccia detritus	EBay	VI	0.7	C	Very Low
30. Qsa	Santa Clara Formation--clay	EBay	III	1.6	C	Very Low
31. Qsc w/a	Santa Clara Formation--andesite	EBay	VII	-0.2	A	Very Low
32. Qsc w/b	Santa Clara Formation--basalt	EBay	VII	-0.2	A	Very Low
33. QThg	Huichica and Glen Ellen Formation	NC; NE	VI, I	0.8	C	Very Low
34. QTge	Glen Ellen Formation	NW	VI, I	0.8	C	Very Low
35. QTget	Glen Ellen Formation with tuff	NW	VI, I	0.8	B	Very Low
36. QTc	Cache Formation	NC	I	1.0	C	Very Low
37. QTl	Livermore Gravel	EBay	III, IV, V, VI	1.2	B	Very Low

Map Symbol(s)	Geologic Unit	Source Map	Seismic Units Present	Average Predicted Shaking Intensity Increment	Landslide Susceptibility	Liquefaction Susceptibility
38. QTt	Tassajara Formation	EBay	III, IV, V	1.4	C	Very Low
39. QTb	Unnamed olivine basalt lava	EBay	VII	-0.2	A	Very Low
40. bi	Intrusive basalt in QTb	EBay	VII	-0.2	A	Very Low
41. QTp	Paso Robles Formation	EBay	II, V, VI	1.2	C	Very Low
42. Qtm; Tm; Tme (?)	Merced Formation	NW; NC; CMm; SM; SSF; NWSC	I	1.0	C	Very Low
Tertiary Units (Pliocene)						
43. Tp	Pliocene Purisima Formation--undivided	EBay; SWSC; SM	I, II	0.8	C	Very Low
44. Tptu	Pliocene Tunitas Sandstone Member of the Purisima Fm.	SM	I, II	0.8	A	Very Low
45. Tpl	Pliocene Lobitos Mudstone Member of the Purisima Fm.	SM	I	1.0	C	Very Low
46. Tpsg	Pliocene San Gregorio Sandstone Member of the Purisima Formation	SM	I, II	0.8	B	Very Low
47. Tpp	Pliocene Pomponio Siltstone Member of the Purisima Fm.	SM	II, III	0.6	C	Very Low
48. Tpt	Pliocene Tehama Sandstone and Siltstone Member of the Purisima Formation	SM	I, II	0.8	C	Very Low
49. Tor	Pliocene Ohlson Ranch Formation	NW	I	1.0	B	Very Low
50. Tors	Pliocene Ohlson Ranch Formation--sandstone	NW	I	1.0	B	Very Low
51. Torc	Pliocene Ohlson Ranch Formation--conglomerate	NW	IV	1.4	B	Very Low
52. Tpt	Pliocene Tuff of Putah Creek	NE	I, II	0.8	B	Very Low
53. Tlt; Tpl	Pliocene Lawlor Tuff	NE	I, II	0.8	B	Very Low
54. Tp	Pliocene Petaluma Formation--undivided	NC	I, II	0.8	C	Very Low
55. Tps	Pliocene Petaluma Fm.--claystone, siltstone and mudstone	NE; CMm	I, II	0.8	C	Very Low
56. Tpc	Pliocene Petaluma Formation--imbedded gray claystone	NE; CMm	I, II	0.8	C	Very Low
57. Tp (?)	Pliocene Petaluma Formation--questionable	NW	I, II	0.8	C	Very Low
58. Tsv	Pliocene Sonoma Volcanics--undivided	NE; CMm	I, II, III, VII	0.5	A	Very Low
59. Tsr	Pliocene Sonoma Volcanics--rhyolitic lava flows	NC; NE; CMm	IV, V, VI, VII	0.1	A	Very Low
60. Tsri	Pliocene Sonoma Volcanics--rhyolitic plugs and dikes	NC; NE; CMm	II, III, VII	0.3	A	Very Low
61. Tsrs	Pliocene Sonoma Volcanics--soda rhyolite flows	NC	VII	-0.2	A	Very Low
62. Tsrp	Pliocene Sonoma Volcanics--perlitic rhyolite	NC; NE	VII	-0.2	A	Very Low
63. Tsrb	Pliocene Sonoma Volcanics--rhyolitic breccia	NW; NC	VII	-0.2	A	Very Low
64. Tsa	Pliocene Sonoma Volcanics--andesitic to basaltic lava flows	NC; NE, CMm	III, VII	0.2	A	Very Low
65. Tsai	Pliocene Sonoma Volcanics--andesitic to dacitic plugs	NC; NE	VII	-0.2	A	Very Low
66. Tsfd	Pliocene Sonoma Volcanics--basaltic or andesitic lava flows with diatomite	NC	I, VII	0.4	A	Very Low
67. Tsb	Pliocene Sonoma Volcanics--basalt	NW	VII	-0.2	A	Very Low
68. Tst	Pliocene Sonoma Volcanics--pumicitic ash-flow tuff	NC; NE; CMm	I, II, VII	0.5	C	Very Low
69. Tswt	Pliocene Sonoma Volcanics--welded ash-flow tuff	NC; NE	II, VII	0.2	A	Very Low
70. Tstx	Pliocene Sonoma Volcanics--tuff (?), welded, massive, hard, xenolithic	NC	VII	-0.2	A	Very Low
71. Tsag	Pliocene Sonoma Volcanics--agglomerate	NC; NE	II, III	0.6	B	Very Low
72. Tslt	Pliocene Sonoma Volcanics--tuff breccia	NC; NE	II, III, VI	0.4	B	Very Low
73. Tsft	Pliocene Sonoma Volcanics--pumicitic ash-flow tuff with lava flows	NC	I, II, VII	0.5	B	Very Low
74. Tss	Pliocene Sonoma Volcanics--sedimentary deposits	NC; NE	VI, I, II	0.8	C	Very Low
75. Tssd	Pliocene Sonoma Volcanics--diatomite	NC; NE	I, II, VI	0.6	A	Very Low
76. rh	Pliocene rhyolite; includes the Alum Rock Rhyolite and Leona Rhyolite	EBay; Oak; WAla	III, IV, V, VI, VII	0.2	A	Very Low

Map Symbol(s)	Geologic Unit	Source Map	Seismic Units Present	Average Predicted Shaking Intensity Increment	Landslide Susceptibility	Liquefaction Susceptibility
77. Tb; Tbu	Pliocene unnamed basalt; included basalt in the Orinda Fm.	EBay	II, VI	0.4	A	Very Low
78. Tri	Pliocene rhyolitic intrusive	EBay	VII	-0.2	A	Very Low
79. a	Pliocene andesitic rock	EBay	VII	-0.2	A	Very Low
80. Tpb	Pliocene Putnam Peak Basalt	NE	VII	-0.2	A	Very Low
81. Tcu	Pliocene Contra Costa Group--undivided	Oak	I, II, IV	0.7	C	Very Low
82. Tbp	Pliocene Bald Peak Basalt	EBay; Oak	II, VII	0.2	A	Very Low
83. Ts	Pliocene Siesta Formation	Oak	II, III, IV	0.6	C	Very Low
84. Tmb	Pliocene Moraga Formation--basalt and andesite	EBay; Oak	VI, VII	-0.1	A	Very Low
85. Tmt; Tmc	Pliocene Moraga Fm.--clastic rocks, including tuff breccia	EBay; Oak	II, III	0.6	B	Very Low
86. Tps; Tor; Tw; Tpo; Tpth; Tol; Tsc	Pliocene non-marine sedimentary rocks, locally called the Orinda, Wolfskill, Tehama or Oro Loma	NE; CE; EBay; Oak	I, II, III, IV, V	0.5	C	Very Low
87. Tpl	Pliocene lacustrine limestone	EBay	VI	0.0	A	Very Low
88. Tpt	Pliocene tuff and sandstone, including the Pinole Tuff	EBay	III, VI	0.2	B	Very Low
89. Tpc; Tuc	Pliocene non-marine sedimentary rocks, clay with sandstone and conglomerate	EBay	VI, I, II	0.8	C	Very Low
90. Tcg	Pliocene non-marine pebble conglomerate	EBay	VI	0.7	B	Very Low
91. Tus	Pliocene non-marine sandstone	EBay	II, IV	0.5	B	Very Low
92. Te	Pliocene Etchegoin Formation	EBay	I, II	0.8	A	Very Low
Tertiary Units (Plicene/Miocene)						
93. Tsc	Pliocene/Miocene Santa Cruz Mudstone	SM	II, III	0.6	C	Very Low
94. Tsm	Pliocene/Miocene Santa Margarita Sandstone	SM	I, II	0.8	B	Very Low
95. Tvia; Tv	Pliocene/Miocene Quien Sabe Volcanics--intrusive andesitic rocks	EBay; SE	VII	-0.2	A	Very Low
96. Tpx	Pliocene/Miocene sandstone--probably a large clastic dike	CMm	VI	0.0	A	Very Low
97. Tdbc	Pliocene/Miocene Drakes Bay siltstone and mudstone	CMm	II, III	0.6	C	Very Low
98. Tdbs	Pliocene/Miocene Drakes Bay glaucomitic sandstone	CMm	I, II	0.8	B	Very Low
Tertiary Units (Miocene)						
99. Tsm	Miocene sandstone and mudstone in Skaggs and Duncans Mills quadrangles	NW	I, II	0.8	B	Very Low
100. Tn, Tmn	Miocene Neroly Sandstone	NE; CE; EBay	I, II	0.8	A	Very Low
101. Tn (?)	Miocene questionable Neroly Sandstone	NC	I, II	0.8	B	Very Low
102. Tmss; Tmb, Tbr; Tmci	Niocene sandstone, including the Cierbo and Briones Formations	NE; EBay	IV, VI	0.2	A	Very Low
103. Tmbu	Miocene Briones Sandstone--upper member (sandstone)	NE	IV, V, VI	0.2	A	Very Low
104. Tmbm	Miocene Briones Sandstone--middle member (light gray siliceous shale)	NE	II, III	0.6	C	Very Low
105. Tmbl	Miocene Briones Sandstone--lower member (sandstone)	NE	IV, V, VI	0.2	A	Very Low
106. Tmsl	Miocene siltstone with minor sandstone	EBay	III, IV	0.4	B	Very Low
107. Tms	Miocene unnamed sandstone, siltstone and shale	NC	II	0.7	C	Very Low
108. Tmc	Miocene non-marine clay	EBay	II	0.7	C	Very Low
109. Tmsa	Miocene tan fine-grained sandstone, local basal conglomerate	EBay	II, IV	0.5	B	Very Low
110. Ttv	Miocene dacite and rhyolite dacite tuff breccia	SWSC	III, IV, VII	0.2	A	Very Low
111. Tus	Miocene unnamed sandstone	SM; NWSC	I	1.0	B	Very Low
112. Tmsh; Tmc; Tma; Tm	Miocene silty-siliceous gray shale (including the Monterey Shale & upper Claremont Shale)	EBay; SWSC; SM; NWSC	II, III	0.6	C	Very Low
113. Tt	Miocene Tice Shale	Oak	II, III, V	0.5	B	Very Low

Map Symbol(s)	Geologic Unit	Source Map	Seismic Units Present	Average Predicted Shaking Intensity Increment	Landslide Susceptibility	Liquefaction Susceptibility
114. Tmsc; Tmi	Miocene brittle cherty-siliceous shale (including the Claremont Shale and lower Claremont Shale)	EBay; Oak	II, III, IV	0.5	C	Very Low
115. Tms; Tmso	Miocene basal sandstone (including the Sobrante Sandstone & Temblor Sandstone)	EBay; SWSC; Oak	IV, V, VI	0.2	A	Very Low
116. Ts; Tmsr	Miocene sandstone (including the San Ramon Formation)	NE; EBay	III, IV	0.4	B	Very Low
117. Tpm	Miocene Page Mill Basalt	SM; NWSC	III, IV, V, VI, VII	0.2	A	Very Low
118. Tmsu	Miocene unnamed graywacke sandstone	EBay	I, II	0.8	A	Very Low
Tertiary Units (Miocene/Oligocene)						
119. Tuv	Miocene/Oligocene unnamed volcanic rocks	SM	III, IV, V, VI, VII	0.2	A	Very Low
120. Tls	Miocene/Oligocene Lambert Shale and San Lorenzo Fm.	SM; NWSC	I	1.0	C	Very Low
121. Tla	Miocene/Oligocene Lambert Shale	SWSC; SM; NWSC	II, III	0.6	C	Very Low
122. Tmb	Miocene/Oligocene Mindego Basalt and related volcanic rocks	SM; NWSC	III, IV, V, VI, VII	0.2	A	Very Low
123. Tlo	Miocene/Oligocene Lompico Sandstone	SWSC; SM	V	0.2	A	Very Low
124. Tvq	Miocene/Oligocene Vaqueros Sandstone	SWSC; SM; NWSC	V	0.2	A	Very Low
125. Tb	Miocene/Oligocene basalt and diabase flow and sills	SWSC; SE	VII	-0.2	A	Very Low
126. Tui	Miocene/Oligocene unnamed marine shale--siliceous and clay shale	EBay	II, III	0.6	C	Very Low
127. Tuc	Miocene/Oligocene unnamed marine shale--clay shale and minor sandstone	EBay	II, III	0.6	C	Very Low
Tertiary Units (Oligocene)						
128. Tkt	Oligocene Kirger Formation--tuff	EBay	II	0.7	C	Very Low
129. Tks	Oligocene Kirger Formation--tuffaceous sandstone	EBay	I, II	0.8	B	Very Low
Tertiary Units (Oligocene/Eocene)						
130. Tsl	Oligocene/Eocene San Lorenzo Formation	SWSC; SM; NWSC	I	1.0	C	Very Low
131. Tsr	Oligocene/Eocene Rices Mudstone Member of the San Lorenzo Formation	SWSC; SM; NWSC	I	1.0	C	Very Low
132. Tst	Oligocene/Eocene Twobar Shale Member of the San Lorenzo Formation	SWSC; SM	I	1.0	C	Very Low
Tertiary Units (Eocene)						
133. Tb	Eocene Butano Sandstone south of La Honda	SWSC; SM; NWSC	II, III, IV, V, VI	0.3	A	Very Low
134. Tb	Eocene Butano Sandstone north of La Honda	SM	II, III, IV, V, VI	0.3	A	Very Low
135. Tbs	Eocene shale in the Butano Sandstone	SWSC; SM	I	1.0	C	Very Low
136. Tb?	Eocene Butano Sandstone--questionable	SM; NWSC	I	1.0	B	Very Low
137. Tt	Eocene Tolman Formation--sandstone and siltstone	EBay	IV, V	0.2	B	Very Low
138. Tk	Eocene Kreyenhagen Formation	NE; EBay	I, II	0.8	C	Very Low
139. Tksh	Eocene Kreyenhagen Formation--semi-siliceous shale	NE; EBay	II	0.7	C	Very Low
140. Tkm; Tem, Tmk	Eocene Markley Sandstone of Kreyenhagen Formation	NE; CE; EBay	I, II	0.8	A	Very Low
141. Tems; Tmu	Eocene Markley Sandstone of Kreyenhagen Formation--Upper sandstone unit	NE; EBay	I, II	0.8	A	Very Low
142. Tml	Eocene Markley Sandstone of Kreyenhagen Formation--lower sandstone unit	CE	I, II	0.8	A	Very Low
143. Tkn; Tnv	Eocene Nortonville Shale of Kreyenhagen Formation	NE; CE; EBay	II	0.7	C	Very Low
144. Tenu	Eocene Nortonville Shale of Kreyenhagen Formation--upper shale unit	NE	II	0.7	C	Very Low
145. Tenm	Eocene Nortonville Shale of Kreyenhagen Formation--middle sandstone unit	NE	II, V	0.4	B	Very Low
146. Ten?	Eocene Nortonville Shale of Kreyenhagen Formation--lower shale unit	NE	II	0.7	C	Very Low

Map Symbol(s)	Geologic Unit	Source Map	Seismic Units Present	Average Predicted Shaking Intensity Increment	Landslide Susceptibility	Liquefaction Susceptibility
147. Tds; Ted; Td	Eocene Domengine Sandstone--tan, arkosic	NC; NE; CE; EBay	I, V	0.6	A	Very Low
148. Tec	Eocene Capay Formation--brown and gray shale and sandy mudstone	NE	II, III	0.6	C	Very Low
149. Tmg	Eocene Meganos Formation--undivided; some parts queried	EBay	I, II	0.8	C	Very Low
150. Tmge; Tme	Eocene Meganos Formation--Division E, greenish gray marine silty mudstone	CE; EBay	II	0.7	C	Very Low
151. Tmgd; Tmd	Eocene Meganos Formation--Division D, light gray marine sandstone	CE; EBay	V, I, II	0.9	B	Very Low
152. Tmgc; Tmc	Eocene Meganos Formation--Division C, bluish gray marine shale; many sandstone interbeds locally mapped	CE; EBay	I, II	0.8	C	Very Low
153. Tmgs; Tmcs	Eocene Meganos Formation--sandstone interbeds locally mapped within Division C	EBay	I, II	0.8	B	Very Low
154. Tmga; Tma	Eocene Meganos Formation--Divisions A and B, basal grayish brown marine sandstone	CE; EBay	I, II	0.8	B	Very Low
155. Tmgs	Eocene sandstone within Meganos Formation	EBay	I, II	0.8	B	Very Low
156. Tts	Eocene Tesla Formation	EBay	II	0.7	B	Very Low
157. Tss	Eocene Tesla Formation--medium-grained sandstone, minor clay shale	EBay	II	0.7	C	Very Low
158. Tss	Eocene unnamed sandstone and shale	Oak	II, VI	0.4	B	Very Low
159. Tss	Eocene unnamed sandstone and shale in southwest Santa Clara County	EBay; SWSC	II, III, IV, VI	0.4	C	Very Low
160. Tss; Ts	Eocene unnamed sandstone in SW Santa Clara County	SWSC	II	0.7	B	Very Low
161. Tls	Eocene unnamed limestone in SW Santa Clara County	SWSC	III, IV, VII	0.2	A	Very Low
Tertiary Units (Eocene/Paleocene)						
162. Tsh; Tssh	Eocene/Paleocene marine shale and micaceous shale in southwest Santa Clara County	EBay; SWSC	II	0.7	C	Very Low
163. Tg	Eocene/Paleocene strata of German Rancho	NW	IV, V, VI	0.2	A	Very Low
Tertiary Units (Paleocene)						
164. Tss	Paleocene unnamed sandstone and shale	SM	III, IV, VI	0.3	B	Very Low
165. Tpu	Paleocene unnamed shale with sandstone	NE	II	0.7	C	Very Low
166. Tpus	Paleocene unnamed shale--upper sandstone member	NE	II	0.7	B	Very Low
167. Tmz	Paleocene Martinez Formation	NE; EBay	II	0.7	C	Very Low
168. Tpmu	Paleocene Martinez Formation--upper member; silty mudstone and shale	NE	II	0.7	C	Very Low
169. Tpm?	Paleocene Martinez Formation--lower member; sandstone	NE; EBay	II	0.7	B	Very Low
170. Tp	Paleocene Pinehurst Shale	Oak	II, III	0.6	B	Very Low
171. Tv	Paleocene Vacaville Shale of Merriam and Turner	NC	II	0.7	C	Very Low
172. Tl	Paleocene Laird Sandstone	CMm	IV, V, VI	0.2	A	Very Low
173. Tpr	Paleocene conglomerate at Point Reyes	CMm	V, VI	0.1	A	Very Low
Tertiary (Paleocene)/Cretaceous Units						
174. TKpr	Lower Tertiary/Upper Cretaceous Pinehurst Shale and Redwood Canyon Formation	Oak	II, III, IV, V	0.4	C	Very Low
175. TKu	Lower Tertiary/Upper Cretaceous undifferentiated sandstone, mudstone and conglomerate of Stewards Point quadrangle	NW	II, IV, V	0.4	B	Very Low
176. TKpr	Lower Tertiary/Upper Cretaceous unnamed shale; marine clay shale and minor thin sandstone of Santa Clara County	EBay; SWSC	II, III	0.6	C	Very Low
177. TKss	Lower Tertiary/Upper Cretaceous unnamed marine arkosic sandstone of Santa Clara County	SWSC	V, II	0.9	B	Very Low
178. KTsh; KTs	Lower Tertiary/Upper Cretaceous unnamed micaceous clay shale, siltstone	EBay; SE	II, III	0.6	C	Very Low
179. KTs	Lower Tertiary/Upper Cretaceous sandstone within unnamed shale, siltstone	EBay	III, IV, V	0.3	A	Very Low
180. KTsh with circles	Lower Tertiary/Upper Cretaceous conglomerate within unnamed shale, siltstone	EBay	V	0.2	A	Very Low

Map Symbol(s)	Geologic Unit	Source Map	Seismic Units Present	Average Predicted Shaking Intensity Increment	Landslide Susceptibility	Liquefaction Susceptibility
181. KTsh with dashes	Lower Tertiary/Upper Cretaceous limestone within unnamed shale, siltstone	EBay	VI	0.0	A	Very Low
Cretaceous Units						
182. Ku	Upper Cretaceous rocks, undivided Great Valley Sequence	Oak	II, III, IV, V	0.4	C	Very Low
183. Kss	Upper Cretaceous marine sandstone and shale in southwest Santa Clara County	SWSC	II, III, VI	0.4	C	Very Low
184. Ksh	Upper Cretaceous marine micaceous shale in southwest Santa Clara County	SWSC	IV, V, VI	0.2	C	Very Low
185. Kcg	Upper Cretaceous marine pebble conglomerate in southwest Santa Clara County	SWSC	V, VI	0.1	A	Very Low
186. Kcg	Cretaceous conglomerate and sandstone, unnamed	EBay	V, VI	0.1	A	Very Low
187. Ksh	Cretaceous dark shale, unnamed	EBay	II, III	0.6	C	Very Low
188. Ka	Cretaceous strata of Anchor Bay	NW	II, IV, VI	0.3	B	Very Low
189. Ks	Cretaceous strata of Stewards Point	NW	II, IV, VI	0.3	B	Very Low
190. Ksb	Cretaceous spilite (sodic basalt) near Black Point on Stewards Point quadrangle	NW	VII	-0.2	A	Very Low
191. Kpp	Cretaceous Pigeon Point Formation	SM	V, VI	0.1	A	Very Low
192. Kgr	Cretaceous granitic rocks of Montara Mountain	SM	VII	-0.2	A	Very Low
193. Kgr	Cretaceous granitic rocks at Bodega Head	NW	VII	-0.2	A	Very Low
194. gr; Kgr	Cretaceous granitic rocks in Marin County	CMm	VII	-0.2	A	Very Low
195. Ksh	Cretaceous unnamed shale	SM	I	1.0	C	Very Low
196. KJgv	Cretaceous/Jurassic Great Valley Sequence undifferentiated	NW	II, III, IV, V	0.4	B	Very Low
197. Km	Cretaceous Great Valley Seq. Moreno Shale--clay shale	CE; EBay	II, III	0.6	C	Very Low
198. Kms	Cretaceous Great Valley Seq. Moreno Shale--sandstone	CE; EBay	II, VI	0.4	B	Very Low
199. Kmi	Cretaceous Great Valley Sequence Moreno Shale--semi-siliceous shale	EBay	II, III	0.6	C	Very Low
200. Kps (also Kj)	Cretaceous Great Valley Sequence Panoche Formation buff arkosic sandstone, minor shale	CE; EBay	III, IV, V, VI	0.2	A	Very Low
201. Kpc	Cretaceous Great Valley Sequence Panoche Formation--cobble conglomerate and sandstone	EBay	V, VI	0.1	A	Very Low
202. Kp (also Kmu)	Cretaceous Great Valley Sequence Panoche Formation--micaceous shale, minor thin sandstone beds	CE; EBay	II, III	0.6	C	Very Low
203. Kpl	Cretaceous Great Valley Sequence Panoche Formation--marine clay shale, minor sandstone	EBay	IV, V	0.2	C	Very Low
204. Kdv	Cretaceous Great Valley Sequence Deer Valley Formation--arkosic sandstone	CE; EBay	IV, V	0.2	A	Very Low
205. Ks	Cretaceous Great Valley Seq. unnamed marine clay shale	EBay	IV, V	0.2	C	Very Low
206. Ksh	Cretaceous Great Valley Sequence marine micaceous shale, undivided	EBay	II, III, IV	0.5	C	Very Low
207. Kcg; cg	Cretaceous Great Valley Sequence conglomerate younger than marine shale	EBay	V	0.2	A	Very Low
208. Kshu	Cretaceous Great Valley Seq. Berryessa Fm., undivided	EBay	III, IV, V, VI	0.2	B	Very Low
209. Kshb	Cretaceous Great Valley Sequence shale within the Berryessa Formation	EBay; SE	III, IV	0.4	C	Very Low
210. Ksg	Cretaceous Great Valley Sequence sandstone and conglomerate within the Berryessa Formation	EBay	VI	0.0	A	Very Low
211. Kss	Cretaceous Great Valley Sequence sandstone within the Berryessa Formation	EBay	V, VI	0.1	A	Very Low
212. Kr	Cretaceous Great Valley Sequence Redwood Canyon Fm.	Oak	IV, V	0.2	C	Very Low
213. Ks	Cretaceous Great Valley Sequence Shephard Creek Fm.	Oak	II, III	0.6	C	Very Low
214. Kcg; Kcgo	Cretaceous Great Valley Sequence Oakland Conglomerate	EBay; SE; Oak	IV, V	0.2	A	Very Low

Map Symbol(s)	Geologic Unit	Source Map	Seismic Units Present	Average Predicted Shaking Intensity Increment	Landslide Susceptibility	Liquefaction Susceptibility
215. Kjm	Cretaceous Great Valley Sequence Joaquin Miller Fm.	Oak	III, IV, V	0.3	B	Very Low
216. Ku	Cretaceous Great Valley Sequence unnamed formation sandstone and shale, undivided	NE	II, III, VI	0.4	C	Very Low
217. Kuu	Cretaceous Great Valley Sequence unnamed formation--upper sandstone member	NE	II, VI	0.4	B	Very Low
218. Kul	Cretaceous Great Valley Sequence unnamed formation--lower shale member	NE	II, III	0.6	C	Very Low
219. Kfo	Cretaceous Great Valley Sequence Forbes Fm. of Kirby	NE	IV	0.3	C	Very Low
220. Kg	Cretaceous Great Valley Sequence Guida Fm. of Kirby	NE	III, V, VI	0.2	A	Very Low
221. Kf	Cretaceous Great Valley Sequence Funks Fm. of Kirby	NE	V, VI	0.1	A	Very Low
222. Ks	Cretaceous Great Valley Sequence Sites Fm. of Kirby	NE	III, V, VI	0.2	A	Very Low
223. Ky	Cretaceous Great Valley Sequence Yolo Fm. of Kirby	NE	III, V, VI	0.2	A	Very Low
224. Kv	Cretaceous Great Valley Sequence Venado Fm. of Kirby	NC; NE	VI	0.0	A	Very Low
225. Kgvs	Cretaceous Great Valley Sequence unnamed sandstone, mudstone, shale and conglomerate	NC; NE	IV, V, VI	0.2	C	Very Low
Cretaceous/Jurassic Units						
226. KJgvm	Cretaceous/Jurassic Great Valley Sequence unnamed fm.--mudstone, shale, siltstone, sandstone and conglomerate	NC; NE	II, III	0.6	C	Very Low
227. KJgrs	Cretaceous/Jurassic Great Valley Sequence siltstone with minor sandstone	NW	II, III	0.6	B	Very Low
228. KJv	Cretaceous/Jurassic unnamed volcanic rocks	SM	III, IV, V, VI, VII	0.2	A	Very Low
229. KJs	Cretaceous/Jurassic unnamed sandstone	SM	V, VI	0.1	A	Very Low
230. KJs	Cretaceous/Jurassic shale in SW Santa Clara County	SWSC	IV	0.3	C	Very Low
231. KJa	Cretaceous/Jurassic argillite in SW Santa Clara County	SWSC	IV	0.3	A	Very Low
232. Kshl; JKk	Cretaceous/Jurassic Great Valley Sequence Knoxville Formation shale with sandstone	EBay; Oak; WAla	II, III, IV	0.5	C	Very Low
233. JKc	Cretaceous/Jurassic Great Valley Sequence Knoxville Formation conglomerate and sandstone	EBay	III, IV	0.4	A	Very Low
234. Jk	Cretaceous/Jurassic Great Valley Sequence Knoxville Formation siltstone	NC	IV	0.3	A	Very Low
235. Jk	Cretaceous/Jurassic Great Valley Sequence Knoxville Formation mudstone and shale	NE	IV	0.3	C	Very Low
236. KJgvc	Cretaceous/Jurassic Great Valley Sequence Novato Conglomerate and unnamed conglomerate	NW; CMrn	IV, V	0.2	A	Very Low
237. KJgv	Cretaceous/Jurassic Great Valley Sequence sandstone with claystone	CMrn	III, IV, V, VI	0.2	C	Very Low
238. KJgvs	Cretaceous/Jurassic Great Valley Sequence sandstone, shale and conglomerate	CMrn	III, IV, V	0.3	A	Very Low
239. bd	Cretaceous/Jurassic basalt and diabase	SWSC	VII	-0.2	A	Very Low
240. vb	Cretaceous/Jurassic volcanic rocks	EBay	VII	-0.2	A	Very Low
241. vb	Cretaceous/Jurassic basalt in SW Santa Clara County	SWSC	VII	-0.2	A	Very Low
242. vd	Cretaceous/Jurassic diorite in SW Santa Clara County	SWSC	VII	-0.2	A	Very Low
243. KJsp; Jsp	Cretaceous/Jurassic Great Valley Sequence sedimentary serpentine	NC; NE	II, III, IV	0.5	C	Very Low
244. Jv	Jurassic basaltic pillow lava and breccia at the base of the Great Valley Sequence	NW; NC; NE	III, VI, VII	0.1	A	Very Low
245. Jd	Jurassic diabase, gabbro, etc. at the base of the Great Valley Sequence	NW	VII	-0.2	A	Very Low
246. Ju	Jurassic ultramafic rock at the base of the Great Valley Seq.	NW	III, VII	0.2	A	Very Low

Map Symbol(s)	Geologic Unit	Source Map	Seismic Units Present	Average Predicted Shaking Intensity Increment	Landslide Susceptibility	Liquefaction Susceptibility
Cretaceous/Jurassic Franciscan Assemblage and Small Masses						
247. KJf	Cretaceous/Jurassic Franciscan Assemblage, undifferentiated	EBay; SM; NWSC; WAla	II, III, IV, V, VI, VII	0.2	C	Very Low
248. KJfss; fs; gwy; KJfs; KJs	Cretaceous/Jurassic Franciscan Assemblage, graywacke sandstone, some local shale	NW; CMm; EBay; SE; SM; SSF; NSF; Oak; NWSC; WAla	III, VI	0.2	C	Very Low
249.KJsh	Cretaceous/Jurassic Franciscan Assemblage, shale with some sandstone	NSF; NWSC; WAla	III	0.5	C	Very Low
250. KJfg; fg; gs	Cretaceous/Jurassic Franciscan Assemblage greenstone	NW; NC; NE; CMm; EBay; SE; SM; SSF; NSF; Oak; NWSC; WAla	VII	-0.2	A	Very Low
251. KJfm	Cretaceous/Jurassic Franciscan Assemblage metagraywacke and other metamorphic rocks	NW; NC; NE; CMm; SE; NSF	VII	-0.2	A	Very Low
252. KJfs; fsr; KJu	Cretaceous/Jurassic Franciscan Assemblage melange or sheared rocks	NW; NC; NE; CMm; EBay; SE; SM; SSF; NSF; NWSC	II, III, IV, V, VI	0.3	C	Very Low
253. fm; KJfm	Cretaceous/Jurassic Franciscan Assemblage metamorphic rocks	EBay; SM; SSF; Oak	VII	-0.2	A	Very Low
254. br	Cretaceous/Jurassic fault (?) breccia	EBay	II, III	0.6	C	Very Low
255. r	Cretaceous/Jurassic Franciscan Assemblage hard monolithic fragments	EBay	VII	-0.2	A	Very Low
256. ch & gs	Cretaceous/Jurassic chert and greenstone	CMm	III, VII	0.2	B	Very Low
257. mch	Cretaceous/Jurassic metachert	NE	III	0.5	C	Very Low
258. ch; fc; KJfc	Cretaceous/Jurassic Franciscan Assemblage chert	NW; NC; NE; CMm; EBay; SE; SM; SSF; NSF; Oak; NWSC; WAla	III	0.5	C	Very Low
259. mgs	Cretaceous/Jurassic greenstone and schistose rocks	NE	II, III, VII	0.3	A	Very Low
260. m, pKm	Cretaceous/Jurassic and pre-Cretaceous high-grade metamorphic rocks	NW; NC; NE; CMm; SE	IV, V, VI, VII	0.1	A	Very Low
261. gl	Cretaceous/Jurassic glaucophane schist	EBay	III, IV, V, VI, VII	0.2	A	Very Low
262. m	Cretaceous/Jurassic marble and hornfels	SM	IV, V, VI, VII	0.1	A	Very Low
263. fl	Cretaceous/Jurassic Franciscan Assemblage limestone	SM; EBay; NWSC; WAla	IV, V, VI, VII	0.1	A	Very Low
264. tr	Cretaceous/Jurassic travertine	EBay	IV, V, VI, VII	0.1	A	Very Low
265. sc	Cretaceous/Jurassic silicacarbonate rocks	NW; NC, CMm; EBay	III, IV, V, VI, VII	0.2	A	Very Low
266. ////	Cretaceous/Jurassic hydrothermally altered rocks	CMm	III, IV, V, VI	0.2	C	Very Low

Map Symbol(s)	Geologic Unit	Source Map	Seismic Units Present	Average Predicted Shaking Intensity Increment	Landslide Susceptibility	Liquefaction Susceptibility
267. fcg	Cretaceous/Jurassic Franciscan Assemblage conglomerate	CMrn; SM	III, IV, V, VI	0.2	A	Very Low
268. sp	Cretaceous/Jurassic serpentine or serpentinite	NW; NC; NE; CMrn; EBay; SE; SM; SSF; NSF; Oak; NWSC; WAla	II, III, IV, V, VI	0.3	C	Very Low
269. spr	Cretaceous/Jurassic serpentine rubble	EBay	II, III, IV, V, VI	0.3	C	Very Low
270. db	Cretaceous/Jurassic diabase	EBay	VII	-0.2	A	Very Low
271. an	Cretaceous/Jurassic andesite	EBay	VII	-0.2	A	Very Low
272. gb	Cretaceous/Jurassic gabbrodiabase	EBay; NSF; Oak	VII	-0.2	A	Very Low
273. ##	Cretaceous/Jurassic foliate metabasalt	NW	III, VII	0.2	A	Very Low
274. mi	Cretaceous/Jurassic mafic intrusive rocks (gabbro & diorite)	NC	VII	-0.2	A	Very Low
275. vk	Cretaceous/Jurassic kertophyre	EBay	VII	-0.2	A	Very Low
276. di	Cretaceous/Jurassic diorite and diabase	EBay	VII	-0.2	A	Very Low
277. qg	Cretaceous/Jurassic hornblende quartz-gabbro	EBay	VII	-0.2	A	Very Low

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